Instructor's Guide for

Organic Chemistry
A Guided Inquiry

A Moog/Spencer Guided Inquiry Course

Andrei Straumanis

Houghton Mifflin Company Boston New York

Foreword on Guided Inquiry Learning*

by Rick Moog, Jim Spencer and John Farrell, authors of *Chemistry: A Guided Inquiry*[1] (for General Chemistry) and two volumes of *Physical Chemistry: A Guided Inquiry*[2].

These guided activities were written because much research has shown that more learning takes place when the student is actively engaged, and ideas and concepts are developed by the student, rather than being presented by an *authority* — a textbook or an instructor.[3] The *ChemActivities* presented here are structured so that information is presented to the reader in some form (an equation, a table, figures, written prose, etc.) followed by a series of Critical Thinking Questions which lead the student to the development of a particular concept or idea. Whenever possible, data are presented *before* a theoretical explanation, and the Critical Thinking Questions lead the student through the thought processes which results in the construction of a particular theoretical model. This is what makes these guided activities a “guided inquiry.” We have tried to mimic the scientific process as much as possible throughout. Students are often asked to make predictions based on the model that has been developed up to that point, and then further data or information is provided which can be compared to the prediction. It is important that these predictions be made BEFORE proceeding to get the full appreciation and benefit of this way of thinking. In this way, models can be confirmed, refined, or refuted, using the paradigm of the scientific method.

There are several articles in the literature by Moog, Spencer, and Farrell about guided inquiry.[4,5,6] *Of particular relevance is a recent article by Jim Spencer describing the philosophical and pedagogical underpinnings of guided inquiry.*[7]

*Topics marked with an asterisks in this *Instructor’s Guide* were adapted from the *Instructor’s Guide for Physical Chemistry: A Guided Inquiry* by Moog, R.S., Spencer, J.N., and Farrell, J.J., 2003, Houghton-Mifflin Co., Boston.

---

[1] Moog, R.S, Farrell, J.J., *Chemistry: A Guided Inquiry, 2nd Edition*, John Wiley & Sons, New York, 2003.

[2] Moog, R.S, Spencer, J.N., Farrell, J.J., *Physical Chemistry: A Guided Inquiry*: *Atoms, Molecules, and Spectroscopy*, and *Physical Chemistry: A Guided Inquiry: Thermodynamics,* Houghton-Mifflin Co., Boston, 2003.

[3] Johnson, D. W. ; Johnson, R. T. *Cooperative Learning and Achievement.* In Sharon, S. (Ed.), *Cooperative Learning: Theory and Research,* pp 23-37, New York: Praeger.

[4] Lloyd, B. N.; Spencer, J. N. *J. Chem. Educ.* 1994, *71*, 206.

[5] Gillespie, R. J.; Spencer, J. N.; Moog, R. S. “Demystifying Introductory Chemistry” *J. Chem. Educ.* 1996, *73*, 617. Earlier versions appeared in *New Directions for General Chemistry*, Lloyd, B. W., ed., Washington, DC: Division of Chemical Education of the American Chemical Society, 1994.

[6] Farrell, J.J., Moog, R.S., Spencer, J.N., “A Guided Inquiry General Chemistry Course.” *J. Chem. Educ.*, 1999. 76: 570-574.

[7] Spencer, J. N. “New Directions in Teaching Chemistry.” *J. Chem. Educ.* 1999, *76*, 566.

To the Instructor

The worksheets contained in *Organic Chemistry: A Guided Inquiry* are designed to guide students through discovery of the material found in a standard organic chemistry course. These materials are intended to be used in conjunction with any standard textbook.

Available course materials:

- *Organic Chemistry: A Guided Inquiry*, containing the ChemActivity worksheets
- *Student Solutions Manual*, containing solutions to the homework Exercises
- *Annotated Instructor's Edition*†, containing answers to the in-class problems
- *Instructor's Guide*† (this volume), containing suggestions on how to use the materials, information about each ChemActivity, and sample quizzes

If you have suggestions about how to improve these materials please contact the author at a.r.s@Stanfordalumni.org

Why Use Guided Inquiry In Your Classroom?

It is nice to know that research has established that guided inquiry works.[8] But if you are like me, your choice of a teaching method ultimately depends on 1) your subjective, personal feelings about a method, and 2) the reaction of your students. The following are some of the reasons why I teach using guided inquiry:

- Students like it. In anonymous surveys, greater than 90% say they prefer guided inquiry to lecture. A common reason cited is that guided inquiry is fun, social, and less frustrating than lecture-based courses.
- Figuring out concepts for themselves exposes students to the thrill of discovery, and gives them a sense of ownership over the material.
- There are no snoozers. Working in small groups, it is hard for students to space out, and easier for them to catch up if they do.
- Guided inquiry appears to improve students' confidence, logical reasoning abilities, and communication skills.
- In a guided inquiry classroom I am not the primary source of information, so students see me less as the authority, and more as their guide and collaborator.
- Some students learn best by talking things out; otherslearn best by listening and critiquing their peers. Guided inquiry allows for these and other learning styles.
- I get to spend time observing students interact with one another, so I see what students understand, and what they *misunderstand*. This feedback has greatly improved my course and my skills as a teacher.
- In a guided inquiry classroom students quickly pick up the message that logical thinking and teamwork are prized above getting the "right answer." This creates an open atmosphere in which being wrong is just a stage on the way to being more right. To me, this feels more like real science than the stark absolutes, set out for the sake of clarity, in many textbooks and classrooms.

---

† Available as an Acrobat download at www.hmco.com (for instructors only).

[8] See Forward to this volume by Moog, Spencer and Farrell.

Comments of Faculty Who Have Used These Materials

- *I appreciate the way the ChemActivities develop a concept and then apply it to other situations. I like the focus on conceptual understanding and developing students' ability to reason. This year was a test year for me, and I intend to use the materials again based on my experience.*
  -Dr. Laura Parmentier, **Beloit College**
- *I really enjoyed teaching the course using the ChemActivities. It only took about a week or two for me, and the students, to get used to the group work approach. My overall impression is that the students are orders of magnitude better at "thinking like organic chemists." Their ability to defend an answer with specific data…is much improved compared to my other classes. I'm very much planning to adopt this approach in my general chemistry and introductory chemistry sequences next year.* -Chuck Leland, **Black Hawk Colleg**e
- *I feel that this method helps students "own" the material themselves. My gut reaction so far is that this method will produce students better able to learn for themselves. Thanks for providing me with this opportunity to use GI. I can't begin to explain how refreshing it is for me to teach with this method. I feel the enthusiasm I remember having when I first started! Muchas gracias.*
  -Dr. Karen Glover, **Clarke College**
- *Never before have I felt so fulfilled as a teacher. In addition, never before have I seen so many students so thoroughly engaged in the classroom! I strongly urge all professors with relatively small class sizes to try this approach.* -Dr. Glen Keldsen, **Purdue U. North Central**
- *I am convinced that incorporating the activities into the teaching of organic chemistry helps students gain a far deeper understanding of the structures and reactions that make up organic chemistry, I will certainly be using the materials with future classes!*
  -Dr. Clare Gutteridge, **University of New Hampshire** (now at Navy)

Comments of Guided Inquiry Organic Chemistry Students

- *Class time was actually learning time, not just directly-from-ear-to-paper-and-bypass-brain-writing-down time. Learning the material over the whole term is far easier than not "really" learning it until studying for the tests.*
- *Overall, I was far less stressed than many of my friends who took the lecture class. They basically struggled through everything on their own.*
- *It was hugely beneficial to be able to discuss through ideas as we were learning them; this way it was easy to immediately identify problem areas and work them out before going on.*
- *Shifting the groups was a good idea, that way we were continually exposed to different ways of thinking.*
- *I didn't get tired during class because I was constantly thinking and working instead of in a lecture class where I just listen and get easily tired.*
- *The method of having us work through the material for ourselves – as opposed to being told the information and trying to absorb it - makes it seem natural or intuitive. This makes it very nice for learning new material because then we can reason it out from what we already know.*
- *I felt like I was actually learning the information as I received it, not just filing it for later use. The format helped me retain much more material than I have ever been able to in a lecture class, and the small, group atmosphere allowed me to feel much more comfortable asking questions of both other students and the professor.*
- *Through working in groups it was nice to see where everyone else was in understanding the material (i.e. to know where other people were having trouble too).*
- *We were able to discover how things happened and why for ourselves…instead of being told "this is what will happen if this mixes with this."*

Contents

FOREWORD ON GUIDED INQUIRY LEARNING* I
TO THE INSTRUCTOR III
Why Use Guided Inquiry In Your Classroom? ....*III*
Comments of Faculty Who Have Used These Materials ....*IV*
Comments of Guided Inquiry Organic Chemistry Students....................*IV*
CONTENTS V

SECTION 1: GUIDE TO CLASSROOM USE 1

INTRODUCTION....................1
ENCOURAGING EQUAL PARTICIPATION....................2
ASSIGNMENT OF GROUP MEMBERSHIP....................3
*One Recipe for Assigning Groups** *4*
CHEMACTIVITY STRUCTURE* 4
INSTRUCTOR'S ROLE AS FACILITATOR*....................5
THE ROLE OF TEACHER TALK IN GUIDED INQUIRY....................6
DANGER OF SUPPLYING ANSWERS TO THE CTQS....................7
NOTES ON QUIZZES, EXAMS, AND GRADING 7
CHRONOLOGICAL ACCOUNT OF A TYPICAL CLASS* 8
COLLECTING STUDENT FEEDBACK 9
FITTING THE CHEMACTIVITIES INTO YOUR ALLOTTED CLASS PERIODS 9
75-Minute Classes and Summer Session Classes....................*9*
A Cautionary Note on Timing *10*
SUGGESTED SEQUENCES....................10
First Semester Organic....................*10*
Second Semester Organic *10*
TEXTS AND MODELS 10
ENCOURAGING STUDENTS TO ANSWER THE CENTRAL META-QUESTION.....11
FINAL WORDS OF ADVICE....................11

SECTION 2: CORRELATION WITH THREE TEXTBOOKS 13

EGE, *ORGANIC CHEMISTRY,* 5TH EDITION 13
MCMURRY, *ORGANIC CHEMISTRY,* 5TH EDITION....................16
BROWN & FOOTE, *ORGANIC CHEMISTRY,* 3RD EDITION 20
VOLLHARDT & SCHORE, *ORGANIC CHEMISTRY,* 3RD EDITION....................22

SECTION 3: GUIDE TO INDIVIDUAL CHEMACTIVITIES *(Key New Concepts, Instructor's Notes, Sample Quizzes)*....................25

CHEMACTIVITY 1: BOND ANGLES AND SHAPE....................26
CHEMACTIVITY 2: LEWIS STRUCTURES 29

---

[*] Topics marked with an asterisks in this *Instructor's Guide* were adapted from the *Instructor's Guide for Physical Chemistry: A Guided Inquiry* by Moog, R.S., Spencer, J.N., and Farrell, J.J., 2002, Houghton-Mifflin Co., Boston.

CHEMACTIVITY 3: RESONANCE STRUCTURES 31
CHEMACTIVITY 4: CONFORMERS OF CARBON STRUCTURES 33
CHEMACTIVITY 5: ISOMERS 35
CHEMACTIVITY 6: CYCLOHEXANE 37
CHEMACTIVITY 7: CHIRALITY 40
CHEMACTIVITY 8: ACID-BASE REACTIONS 42
CHEMACTIVITY 9: CORE CHARGE AND INDUCTIVE EFFECTS 45
CHEMACTIVITY 10: RESONANCE EFFECT 47
CHEMACTIVITY 11: ELECTRON ORBITALS 49
CHEMACTIVITY 12: ONE-STEP SUBSTITUTION REACTIONS 51
CHEMACTIVITY 13: CARBOCATIONS AND TWO-STEP SUBSTITUTION REACTIONS 53
CHEMACTIVITY 14: ELIMINATION REACTIONS 57
CHEMACTIVITY 15: STEREOCHEMISTRY OF E2 REACTIONS 60
CHEMACTIVITY 16: SPECTROSCOPY 62
CHEMACTIVITY 17: ELECTROPHILIC ADDITION 65
CHEMACTIVITY 18: EPOXIDE & BROMONIUM RING OPENING 68
CHEMACTIVITY 19: CARBON-CARBON BOND FORMATION 70
CHEMACTIVITY 20: RADICAL HALOGENATION OF ALKANES 72
CHEMACTIVITY 21: ANTI-MARKOVNIKOV ADDITION OF H-BR 74
CHEMACTIVITY 22: HYDROBORATION/OXIDATION 76
CHEMACTIVITY 23: ELECTROPHILIC ADDITION TO ALKYNES 79
CHEMACTIVITY 24: CONJUGATION 81
CHEMACTIVITY 25: AROMATICITY 83
CHEMACTIVITY 26: NMR OF AROMATIC MOLECULES 85
CHEMACTIVITY 27: POLYMERIZATION REACTIONS 87
CHEMACTIVITY 28: DIELS-ALDER REACTIONS 89
CHEMACTIVITY 29: ELECTROPHILIC AROMATIC SUBSTITUTION 91
CHEMACTIVITY 30: SYNTHESIS WORKSHOP I 94
CHEMACTIVITY 31: NUCLEOPHILIC ADDITION TO A CARBONYL 96
CHEMACTIVITY 32: PROTECTING GROUPS 98
CHEMACTIVITY 33: REACTIONS AT THE α CARBON OF A CARBONYL 100
CHEMACTIVITY 34: BASE CATALYZED ALDOL REACTIONS 102
CHEMACTIVITY 35: ACID CATALYZED ALDOL REACTIONS 106
CHEMACTIVITY 36: REACTIONS OF α,β-UNSATURATED COMPOUNDS 108
CHEMACTIVITY 37: MICHAEL REACTION 110
CHEMACTIVITY 38: ACIDITY AND pK_A OF PHENOLS 112
CHEMACTIVITY 39: NUCLEOPHILIC AROMATIC SUBSTITUTION 115
CHEMACTIVITY 40: REACTIONS OF CARBOXYLIC ACIDS 117
CHEMACTIVITY 41: REACTIONS OF ACID CHLORIDES AND ANHYDRIDES 119
CHEMACTIVITY 42: CLAISEN REACTIONS 121
CHEMACTIVITY 43: DECARBOXYLATION 124
CHEMACTIVITY 44: SYNTHESIS WORKSHOP II 126
CHEMACTIVITY 45: AMINES AND AMINO ACIDS 127
CHEMACTIVITY 46: AMINO ACIDS, POLYPEPTIDES AND PROTEINS 130

Section 1: Guide to Classroom Use

Introduction

The following pages describe how guided inquiry materials have been used in the classroom by a variety of instructors. This history is provided as a template to get you started, but to be true to the method you must make guided inquiry your own. The variation of guided inquiry that I use is adapted from the method used in classrooms at Franklin and Marshall College, and their brand of guided inquiry was adapted from other sources. The guided inquiry worksheets are a backbone that can support many different teaching styles. Listen to your instincts and to your students. Build on the suggestions in this document to create your own personal version of guided inquiry. For further reading, you may want to consult the following excellent resources on the subjects of cooperative learning and group problem solving.[9,10,11]

The following is a brief description of three different ways you could use these materials:

- The most popular and effective strategy for using these materials involves devoting most of each class meeting to student group work on a ChemActivity worksheet (groups of three or four students). The instructor serves as facilitator: observing student group work, answering questions, and intervening when necessary. Common interventions include: presenting an interesting answer, leading a whole-class discussion, or delivering a 3-minute summary or mini-lecture. The larger your class, and the faster you wish to push your students through the activity, the more often you will need to address the class (more on this in the section on “Teacher Talk”).
- A good way to get your feet wet is to replace a lecture with group work on a ChemActivity. (Cautionary note: if you portray this as an “experiment” it could undermine its effectiveness.) From here, many faculty never look back, others continue to cover some topics using a ChemActivity, and some topics using interactive lectures. Several faculty have tried mixing lectures and group work by having a summary lecture at the end of several class periods of group work. At first glance, this is an appealing option. The danger in doing this is that students may get the message that they can hold out for “the answers” which are eventually coming from “the authority,” and this may degrade their willingness to struggle toward answers of their own.
- If giving up a whole lecture is too drastic, you may choose to excerpt key questions from a ChemActivity and use them during your lecture as short group-work problems.

---

[9] Bruffee, Kenneth A. *Collaborative Learning: Higher Education, Interdependence, and the Authority of Knowledge.* Baltimore: Johns Hopkins Press, 1993.

[10] Johnson, D. W.; Johnson, R. T; Smith, K. A. *Active Learning: Cooperation in the College Classroom*; Interaction: Edina, MN, 1991.

[11] A variety of useful information on cooperative learning is available through Pacific Crest Software, Corvallis, OR. They offer *A Handbook on Cooperative Learning* along with other resources including workshops and teaching institutes. http://www.pcrest.com

Encouraging Equal Participation

One of the great challenges of using groups is trying to generate equal participation among group members. Many guided inquiry classrooms employ formal roles (described below). Usually roles are rotated every class meeting so that every student experiences each role and its responsibilities. Some instructors have had success rotating roles less frequently, and I know of one instructor who assigns roles (based on student personalities) and keeps them for the life of a group.

In small classrooms (less than 12 students), roles seem to be less necessary. Typically, in a very small class the instructor is aware of almost everything that is happening in their two or three groups. This knowledge can be used to informally encourage equal participation. For example, a question may be posed directly to a less active student. Similarly, the instructor can call on certain individuals to present information at the board, or to serve as spokesperson for the group.

In large classrooms (>40 students) the management of roles takes extra effort. In my large classes (up to 75 students) I have resorted to informal means of encouraging equal participation, mostly because I was unable to manage roles effectively. In classrooms of any size it is important to discourage the most active students from blurting out answers to questions that are posed to the class or to their group. I usually take such a student aside after class, praise their willingness to participate, and explain the pedagogical value of letting weaker students think about a question before they hear the answer. Such students are great assets, but their participation must to be channeled or they can do more harm than good.

Formal Roles*

The following are the most commonly used roles. Note that a primary means of enforcing the use of roles is to only respond to questions posed by the manager. This encourages valuable internal processing of any questions.

Manager	Manages the group. Ensures that members are fulfilling their roles, that the assigned tasks are being accomplished on time, and that all members of the group participate in activities and understand the concepts. The instructor responds only to questions from the manager (who must raise his or her hand to be recognized).
Presenter	Presents oral reports to the class. These reports should be as concise as possible; the instructor will normally set a time limit.
Recorder	Recorder keeps a record of the group's official answers in his or her workbook. After class the Recorder submits a photocopy[12] of these answers to the instructor. This allows you to keep tabs on all the groups and encourages groups to come to consensus about each answer. The Recorder also notes the names and roles of the group members at the beginning of each day, records how far the group got in the ChemActivity, as well as questions that remain unanswered. On some days you may choose to have them submit the results of

---

[12] In quantitative courses such as general and physical chemistry it is fairly easy to have the recorder submit a complete copy of the groups answers using carbon paper or hand copying. The only effective way I have found to do this in organic chemistry is to have the recorder submit a photocopy of the group's answers.

	group self-assessments such as “list the most important concepts you learned today.” (*Use a recorder only if you intend to give them feedback in response*.)
Reflector	Observes and comments on group dynamics and behavior with respect to the learning process. These observations should be made to the manager on a regular basis (no more than 15 minutes between reports) in an effort to constantly improve group performance. The reflector may be called upon to report to the group (or the entire class) about how well the group is operating (or what needs improvement) and why.

Other roles can be used, but are not described here (e.g., Technician; Encourager; Checker).

Assignment of Group Membership

Instructor assignment of group membership is an opportunity to gain valuable insight into the personalities of your students. The more you know about your students, the better you will be able to push them toward their potentials. For example, a student who is frustrated by the material or the teaching method should be approached differently than a student who is confident and invested.

In general, most instructors try to make the groups heterogeneous with respect to both student performance and gender. The conventional wisdom states that all-female groups tend to work better than all-male groups, and that a group with one female and three males is to be avoided. In assigning group membership, I find myself thinking less about gender and more about quiet vs. loud. For example, I never put one quiet person in a group with three loud people, and some of my most successful groups were the result of putting four quiet, thoughtful students together, or four loud, talky students together.

Assigning group membership gets easier as you collect more information about your students. To speed this process, I periodically ask that each student send me a confidential email detailing who they like to work with, who they do not like to work with, and why. At the beginning of a semester I mix things around every two weeks so that students get to know each other, and experience a variety of learning styles. At mid-semester I usually begin honoring students’ requests regarding ideal group mates.

After the mid-term, I will usually keep a good group together unless a problem arises, or I need to “borrow” a person from a productive group to help “save” a dysfunctional group. My goal is to find an overall arrangement that works best for everyone. Usually, the greatest challenge is finding a place for problem individuals. At times I have been lucky and found a configuration that works well for everyone, but usually I must make someone compromise. If you know your students, you will be able to assess which students will best tolerate being placed in a group with a lazy, argumentative, nit-picking, or disgruntled student. In one desperate situation, I tried putting three non-cooperative students together in a group to protect the other students. It is unlikely you will have to resort to such extreme measures.

Try different arrangements. Often logic can be applied to the process, but just as often you will be surprised by the results.

One Recipe for Assigning Groups*

The following is the recipe for assigning groups found in the *Instructors Guided for Physical Chemistry: A Guided Inquiry* by Moog, Spencer and Farrell.*

First Period Through First Exam

Membership in groups is changed frequently (about every other class period). In the absence of substantive information regarding relative student performance, group members are selected randomly (or in a manner which enables every student to meet and work with every other student). This exposes students to a variety of learning styles and approaches. A computer program may be used to do this, or it can be done by hand depending on the instructor's choice and the size of the class. If most of the students have used this approach in previous courses it is not necessary to change groups as often as stated above.

After the First Exam

Group membership is set by the instructor using a procedure known as "reverse mapping." That is, group 1 is composed of the student with the highest grade on the first exam, the student with the lowest grade on the first exam, and two students from the middle. For group two: the student with the second-highest grade; the student with the second-lowest grade; two students from the middle. This process is repeated until all groups are assigned. This approach tends to produce groups at about the same performance level.

After the Second Exam

Group members are set for this time span as described above, using results from the second exam.

After the Third Exam

As above, or leave groups as they were. Some groups may desire to stay together while others will not. It may be possible to do some shuffling to "satisfy" most of the students.

ChemActivity Structure*

A *ChemActivity* is divided into three components:

- Models can consist of a figure, equations, a table, prose, or any combination of the above. The Model is designed to define or develop some chemical concept. In some cases, Information is presented as background or elaboration for a Model.
- Critical Thinking Questions (CTQs) are crafted to lead the *student* to make inferences and conclusions. The process of answering the CTQs is supposed to reveal fundamental relationships or concepts inherent in the model.
- Exercises are designed to give the students practice in problem solving using the chemical concept(s) discovered during class. They are generally assigned as homework-type problems.

Instructor’s Role as Facilitator*

In a typical guided inquiry classroom students work in groups of three or four *during* most of the class period. Generally, the instructor spends most of the period moving among the groups, observing and listening to the groups’ discussions. For each group, the instructor will examine answers to the CTQs (reading over the shoulder of one or more students). If the students are proceeding at an adequate pace and the answers are reasonable, no intervention is needed; after staying for a brief period of time and listening to the group interaction, the instructor moves on. Occasionally, a question may be posed to one of the group members to make sure that he or she understands the concept. Some care and discretion must be used, however, as this will interfere with the group’s time and dynamics.

If one, or more, of the answers to the CTQs is incorrect, the instructor must make a decision whether to intervene or not. There is a strong temptation to intervene, but this should be avoided if possible. Our experience is that students learn best and retain information longer if they (the group working together) discover the answer; thus, telling the students the answer has little benefit. Here are a few suggestions related to this issue:

- If you think the group will discover their error (via upcoming Models or Critical Thinking Questions), let them proceed. Hopefully, they will then come back and re-examine their incorrectly answered question. This can be checked (by the instructor) at a later time.
- Ask one member of the group to explain the answer in more detail. (Note: This should occasionally be done with correct answers as well so that instructor intervention is not interpreted as indicating a wrong answer.) One or more members of the group will often see the error during the student’s response. If not, the instructor may indicate that there is an error in the analysis, without indicating precisely what it is.
- Tell the Manager that Group 5 (pick a group that has the correct answer) has a different answer. Ask the Manager to send a representative to Group 5 to resolve the differences. Normally, the group with the correct answer will prevail.

If one or more of the students does not seem to understand a concept, it is the instructor’s responsibility to make sure that the Manager is aware of this situation. The Manager should take corrective action: back-tracking the group to that concept; having another member of the group discuss the concept with the student who does not understand; arranging a short group (or mini-group) meeting before the next class period. In some cases, an appropriate solution may be to suggest that the student discuss this issue with the instructor outside of class prior to the next meeting.

Above all, it is important to reinforce the idea that this is a team effort, and that it is in *everyone’s* best interest to ensure that all members of the group understand the material. Students having difficulty with a concept clearly benefit from the explanations of those who have a firmer grasp on the idea. As we know from our experience as instructors, explaining these concepts to others also strengthens and solidifies the understanding of the explainer. In this way, all students in a group benefit from the group interaction. Our experience has been that at various times during the course (and during an individual class meeting), all of the students are at some time the explainer, and at others the listener.

The Role of Teacher Talk in Guided Inquiry

Ideally, work on a ChemActivity is a highly structured, in-class discovery experience that culminates in formulation of a chemical concept. Of course, an individual student, a whole group, or even the whole class may get lost along the way.

The authors of guided inquiry activities have tried to make the road toward the concept d'jour a clearly marked, four-lane highway. It is, therefore, always a disappointment to find a group of students huddled together at the dead-end of a barely discernable path. At these moments, I often choose to move beyond my role as roving observer and facilitator, and intervene more drastically. When several groups are in trouble, I usually choose to intervene via a brief whole-class discussion or mini-lecture.

For me, a typical class period includes several short instructor comments or questions, and ends with a few minutes of instructor led discussion. In general, the better the class is going, the less I say. Another general rule is that the larger the class, the more time I spend at the front of the room, speaking to the class as a whole.

Instructor talk can be useful for speeding student work on an activity. If the progress of a group or the whole class is too slow, I often choose to interrupt group work and give away an answer. This tends to shut down further discussion since the "expert" has ruled in with the "correct" answer. Be aware that your input may have this effect, and that each attempt to speed the class along has a cost. You have to decide which is more beneficial at that moment: to move them toward the main concept waiting at the end of an activity, or to foster discussion and maintain the integrity of their discovery experience.

Given the rhetoric of some guided inquiry practitioners, you might be surprised at how willing I am to give out answers to Critical Thinking Questions (CTQ's) during class. You must use your judgment, augmented by eavesdropping, to decide when most groups have struggled with a question long enough thatit will be beneficial for them to hear an instructor-led discussion, or a statement of an answer.

Whole class discussions can take many forms. I have found this part of the method draws most heavily on my creativity and instincts. Examples include: calling for a student to present the ideas of the group, summarizing answers from each group on the board, leading a discussion of interesting wrong answers, trading student emissaries between groups with conflicting answers, or using a mini-lecture to try and explain away a misconception held by a large number of students.

I have found that intervening too frequently reinforces the commonly held student belief that no answer is correct until confirmed by the instructor. With that said, however, revealing too little can cost you the students' trust. Especially when beginning a new instructional method, frustration thresholds are very low. The number one complaint from guided inquiry students continues to be "the instructor refuses to answer my questions." I have found that explaining the pedagogy (essentially telling students "it is for your own good when I force you to figure out answers for yourselves") only intensifies anxiety and frustration. At the first sign of trouble, I have found it best to at least acknowledge the tricky spot, and perhaps give a hint. This lets the students know you want to help. Ideally, you get to know each student's tolerance threshold so you can give only the minimum information required for that group or individual to figure the concept out for themselves.

According to Piaget, frustration is an important part of learning.[13] The trick is to push students, but not make them snap. Some students have high tolerance for the cognitive discomfort inherent in learning; others do not. It is deeply gratifying to know your students at this level, and very exciting when this knowledge helps you push their limits. In my experience, a traditional lecture environment is not conducive to this type of interaction.

Danger of Supplying Answers to the CTQs

Students clamor for answers. This can become a delicate tug-o-war with a student who is frustrated and insistent (see section on "Teacher Talk"). A guided inquiry organic chemistry course leaves some students feeling very insecure at times. They will say things like "How am I supposed to know if I am learning the 'right' things if you don't tell me what is right and what is wrong?!" One purpose of this type of instruction is to give students the opportunity to develop confidence in their reasoning abilities, and telling them your (or my) answer whenever they ask will interfere with this process. Some guided inquiry instructors believe that it is pedagogically damaging to even give students access to the answers to the homework Exercises. (If you agree, you must ask your bookstore to restrict access to the *Student Solutions Manual*.) Most every instructor agrees that you should restrict student access to the *Annotated Instructors Edition*, which contains answers to the in-class Critical Thinking Questions. (Note that the IAE contains full solutions, written in a voice appropriate for students. In the past, I have given students supervised access to the IAE as part of a review for the final exam.)

Notes on Quizzes, Exams, and Grading

Every period (except the first class period and the period after each hour exam) *begins* with a five-minute quiz. The quiz covers an important concept developed during the previous class meeting. The purposes of the quiz are: to give the instructor some immediate feedback about how well the concept was learned; to reinforce the concept in the student's mind; to encourage the student to do the homework Exercises *before* the quiz is given; to partition the course material into small, manageable sections; to encourage students not to cram for exams; to develop good study habits; to encourage good attendance and on-time arrival. Five minutes is sufficient to do this. Sample quizzes for each activity are provided in Section 3 of this manual.*

For the most part, traditional exams and quizzes have been used in conjunction with guided inquiry materials. You may find that your question writing changes as a result of spending most of each class observing what your students know and do not know. My exams questions have become increasingly focused on concepts, and tend to mimic the structure of a ChemActivity, with a Model followed by questions asking the student to interpret data from the Model. Pre-medical students appreciate this type of exam question since a majority of the MCAT exam is so structured.

Exams and quizzes are taken individually. Quizzes usually account for about 10% of the final grade. I drop the two lowest quiz scores. You may choose to include a 5% group participation grade. Some instructors keep a notebook and record a "+" or "–" next to a student's name each day they demonstrate above or below average participation.

---

[13] Piaget, J. *J. Res. Sci. Teach.* 1964, 2, 176.

Alternatively, you could use confidential peer evaluations to assign a group participation grade. In the past I have done this by asking each student to distribute 9 points among the other three members of the group, stipulating that you can not assign partial points or two people the same number of points (e.g. 3,3,3 and 4,4,1 are not legal, but 2,3,4 and 1,3,5 are allowed). Some students do not enjoy this responsibility, but you could argue that it gives them insight into the difficulties of *your* job evaluating them.

I strongly recommend not using a traditional curving strategy for exams since it may discourage cooperation between students. I use an absolute scale (>90% = A, etc.). If I write a doozie of an exam, I follow it up with an open book, unlimited time, take-home group exam worth ten points, and add the two scores together for each student. This gives students an opportunity to revisit material they had difficulty with, and serves as a more transparent means of curving since most groups score about the same on the take-home.

A collateral benefit of this type of take-home assignment is the formation of permanent out-of-class study groups. For such an exercise, I let the students form their own groups of either three or four. I require that each group turn in an index card with the names of all group members prior to receiving their copy of the exam. (This helps ensure that no one is left out.) I specify that they can consult any published work, but they can only talk to their group-mates or me about the exam. After such an exercise, I observe an increase in the number of out-of-class study groups. For this reason, I always do this type of bonus-exercise after the first exam.

Chronological Account of a Typical Class*

- Before class, the instructor posts a list of student names, (roles) and groups in a prominent location, along with a map indicating where each group will sit.
- When the class begins (start on time!) the instructor hands out the quizzes and gives the students five minutes for completion.
- The instructor collects the quizzes at the end of the five minute period (sharply).
- The instructor dispenses a folder to each Manager. The folder has the graded quizzes from the last class period for each member of the group. The folder may have other materials: recorder's answers from last period; carbon paper for today's recorder; special instructions. (This folder could also be used to deliver the quizzes at the start of the class).
- It is wise to give students a short time (1 - 2 minutes) to discuss the quiz as a group and decide on the correct answer. This can be followed by group reporting of answers or, in the interests of time, instructor reporting of the answers. You may find, if you skip this step, that students spend the first part of class talking about the quiz, anyway.
- Students begin working on the ChemActivity.
- The instructor circulates and examines the answers to the CTQs.
- One or more times during each class the instructor may choose to interrupt group work for some variety of whole-class discussion. This may consist of a Presenter reporting an answer followed by instructor-led discussion of that answer, or any other productive presentation or discussion. This type of interruption is often necessary when students are having difficulty with a topic.

- The groups are stopped when there are five minutes remaining. The instructor may choose to call on a Presenter or deliver a brief summation. Alternatively, students may be given (either individually or as a group) two minutes to write answers to a question such as:

  -What are the two (or three) most important concepts you learned today?

  -What was a strength of your group's performance today?

  -What was an area for improvement?

  -What question do you still have about the material examined today?

  The question should focus on either reinforcing the concept(s) learned, or some aspect of the process of learning. Answers should be placed in the folder along with any Recorder notes.
- The class ends on time. You may find that the students are still discussing the concept, a skill development question, or some aspect of the process as you leave the room.

Collecting Student Feedback

Particularly in your first year of doing this, it can be useful to conduct student assessment two or three times a semester. One strategy is to give students ten minutes of class time to describe "at least one strength" of the course, to suggest "at least one area for improvement," and to make other comments. To ensure anonymity, a student can be assigned to collect the forms and give them to the department secretary, who types them and destroys the originals.*

To reduce typing work, I accomplish the same thing using an anonymous web-based form that emails student responses to the department secretary, who cuts off the headers and gives me the now-anonymous responses. To ensure full participation I ask the secretary to keep a list of all those who respond, and I award bonus points for completing the form. Alternatively, your computer support people can write a script that will deliver you the comments, and deliver the department secretary the name of each responder.

Fitting the ChemActivities into Your Allotted Class Periods

The 46 ChemActivities in *Organic Chemistry: A Guided Inquiry* are broken into one-day sub-activities (called Parts A, B, C etc.) Each of the 82 sub-activities can be completed in a single 50-minute class period. Some activities are easily completed in this time, but a majority will require you to push your students to get them through in 50 minutes. (Strategies for doing this are described in the section on "Teacher Talk," above.) If you are not compelled to cover all the topics, you may choose to spend 1 ½ or 2 class periods on certain key activities.

75-Minute Classes and Summer Session Classes

Guided inquiry is very well suited for the longer class periods typical of summer-sessions and Tuesday-Thursday timeslots, since students are able to keep their focus for a long time in a group-work setting. In my experience, student groups will stay focused for up to two hours without taking a formal break. In many ways it is an advantage to have class periods that are longer than the standard 50 minutes. While this requires you to complete an activity, plus part of another activity, on most days; it allows for continuity on those occasions when you want to devote more time to a single activity, or want to complete several Parts of a ChemActivity in one sitting. Note that you can save some time by having one quiz per class, regardless of the amount of material you covered.

A Cautionary Note on Timing

Often, groups will not complete the activity before the end of class. If most groups are more than 70% finished, the best strategy is to announce that they are responsible for finishing the activity outside of class. Challenging them to complete the activity during or after class will do two things: 1) keep them on task during class and 2) encourage out-of-class group work. (You may want to allow groups a few minutes to figure out a good time to meet outside of class.)

If you plan to spend all or part of the next class working on this same activity, announce the target stopping point well before the end of class. Without a clear (and ambitious) goal, some groups will spend the entire class pondering the first challenging question. You want to avoid a situation where students sense that they can slow the pace of the course, and reduce the overall amount of material covered, by working inefficiently in class. To avoid this, I rarely let work on an activity roll over into the next class period.

Suggested Sequences

A typical semester consists of about forty-one, 50-minute class periods, with at least two periods devoted to mid-term exams. This means, unless you give your mid-term exams outside of scheduled class time, you will not complete all of the 82 sub-activities in the workbook. The following lists activities you might choose to skip, with the remaining activities constituting a suggested minimum sequence for each semester.

First Semester Organic

ChemActivities (CAs) 1-23 comprise a typical Semester I course. An ambitious goal is to complete 41 of the 42 Parts (possibly skipping CA 17, Part D). A minimum treatment would involve skipping CAs 17D, 19, 20A&B, 21, 22A&B and 23. Such a treatment leaves you with a very manageable 34 class periods worth of material. You would probably want to use a couple supplementary sessions to cover certain key topics and reactions scattered throughout the skipped activities. Key topics are detailed for each activity in the Instructor's Notes section of this volume. In general, if you plan to skip an activity, read the Instructor's Notes to see how this activity fits with subsequent activities.

Second Semester Organic

ChemActivities 24-46 comprise a typical Semester II course. If you give only one mid-term you could complete all 40 Parts. A minimum treatment would skip CAs 27, 28, 30, 32, 33B, 35, 36A&B, 37, 43, 44 and 46A&B. Such a sequence leaves you with 27 one-day activities. If you are not compelled to cover all topics, I recommend choosing a less full sequence to give you the luxury of spending extra time on the activities you think are most important.

Texts and Models

Organic Chemistry: A Guided Inquiry is not intended as a substitute for a textbook. Most any standard textbook can be used in conjunction with these materials. I find most organic textbooks are written at a level such that reading in the text serves as an excellent review for students who have already been introduced to the basic concepts via a

ChemActivity. I tell my students that a good goal, and a test of their mastery of a given unit, is whether they can read and understand the assigned sections in the text.

I strongly discourage use of the text as a reference during class since this causes students to hunt for answers to CTQs, rather than coming to their own conclusions. The former would be similar to filling in a crossword puzzle using the answers as reference. I encourage students to read in the text *after* class. Some of the most successful students read in the text after each class to try and confirm their answers to the in-class Critical Thinking Questions. If you have ever waited for tomorrow's paper to check your crossword answers, you know that "expert" answers are extremely interesting if you have spent hours struggling to come up with your own flawed version.

One of the most challenging aspects of organic chemistry is the visualization of molecular structure in three dimensions. The use of models is imperative in this process. Students are asked to make extensive use of models in the first semester activities. I use the Prentice-Hall models or one of the compatible knock-offs. In is useful to have access to a model set with a representation for hybrid orbitals.[14]

Encouraging Students to Answer the Central Meta-Question

On the surface, the students' job is to construct and refine answers to the Critical Thinking Questions, but the real learning takes place when they access the next level and answer the meta-question that underlies most every question in every ChemActivity:

> ***"What is the purpose of this question; what point, distinction or concept is the author trying to convey by asking us this question?"***

Answering this question is often a challenge. It requires a student to see the forest from within the trees, and to get inside the author's mind. I have tried to be very clear, but sometimes even the expert will not see where I am going. To help with this, I have provided the *Instructors Annotated Edition*, with comprehensive answers to the CTQs; and Section 3 of this volume, entitled *Guide to Individual ChemActivities*. Use these resources to help answer the meta-question for yourself, and then encourage your students to use the meta-question to achieve a deeper understanding of the material.

Final Words of Advice

Most students and faculty need a few class periods to find their rhythm with guided inquiry; by mid-semester it should start to really come together; by the second time through, many faculty say they would never go back to lecture. The hardest part appears to be figuring out when to interrupt and what to say when you do. At the beginning you should err on the side of interrupting more often and saying more. Use your instincts. If you think of this as an experiment, do not let on. For your students, this course is a huge deal and you do not want to give the impression that you are "playing around" with their lives. Let the materials guide you, but do not sit on your hands when it comes to answering student questions and getting involved in discussions. Do not sit back and "let the materials do their thing." Each ChemActivity is a guide for getting students to think more and interact more. Beyond that, it is up to you to make it work.

---

[14] Orbital lobe pieces compatible with Prentice-Hall models are available at www.indigo.com/models/

Section 2: Correlation with Three Textbooks

The following section provides full or partial reading assignments and supplementary problems for four organic textbooks: Ege's 5th Edition, McMurry's 5th Edition, Brown and Foot's 3rd Edition, and Vollhardt's 3rd Edition. Most any standard text is appropriate to support guided inquiry instruction.

If you compile a list of readings and problems for a text not listed here, please send it to me (a.r.s@stanfordalumni.org) and I will include it in the next edition of this *Instructor's Guide.*

Ege, *Organic Chemistry*, 5th Edition

ChemActivity 1: Bond Angles and Shape
Part A: Read Chapter 1 through the end of Section 1.3.
Part B: Read Section 1.8.
ChemActivity 2: Lewis Structures
Part A: Read Section 1.4 A&B and 1.5. Do problem 1.23 at the end of Chapter 1
Part B: Read Section 1.4C&D. Do problem 1.22.
ChemActivity 3: Resonance Structures
Part A: Read Sections 1.6.
Part B: Do problem 1.27, 3.33, and 3.34.
ChemActivity 4: Conformers of Carbon Structures
Read Section 5.8.
ChemActivity 5: Isomers of Carbon Structures
Part A: Read Chapter 5 through Section 5.3, Sections 5.5-5.6, 5.9, and 5.10.
Part B: Read Section 6.10.
ChemActivity 6: Potential Energy and Cyclohexane
Read Section 5.11.
ChemActivity 7: Chirality
Part A: Read Chapter 6 through Section 6.6. Do Problems 6.24-6.26.
Part B: Read Sections 6.7-6.9, and 6.11. Do problems 6.27, 6.29, 6.32, 6.33, 6.35, 6.37, 6.38, and 7.43.
ChemActivity 8: Acid-Base Reactions
Read Chapter 3 through Section 3.3, and Section 3.5. Do problems 3.37, 3.38, and 3.40.
ChemActivity 9: The Nucleus and Inductive Effects
Part A: Read Sections 3.4 and 3.7. Do problems 3.27a,b, 3.28, and 3.30.
Part B: Read Section 3.6B. Do problems 3.29, and 3.32.
ChemActivity 10: The Resonance Effect
Read Section 3.6A. Do problems 3.27c,d, 3.39, 16.30, 16.31, and 16.33.
ChemActivity 11: Electron Orbitals
Part A: Read Chapter 2 through Section 2.4. Do problems 2.30, 2.34, and 2.35.
Part B: Read Sections 2.5-2.9. Do problems 2.39, 2.41, and 2.42.
ChemActivity 12: One-Step Nucleophilic Substitution
Part A: Read Chapter 4 through Section 4.2. Do problems 7.27, and 16.25.
Part B: Read Section 13.3 and 13.4. Do problems 7.28, 7.29, and 7.33a,b.
ChemActivity 13: Two-Step Nucleophilic Substitution
Read Chapter 7 through Section 7.6.

ChemActivity 14: Elimination
Do problem 7.30.
ChemActivity 15: Stereochemistry of E2 Reactions
Part A: Read Section 8.7.
Part B: Read Section 7.7. Do problems 7.44 and 7.45.
ChemActivity 16: Spectroscopy
Part A: Read Chapter 12 through Section 12.2. Do problems 12.26 and 12.31.
Part C: Read Sections 5.4, 5.7. Do problems 11.18, and 11.19-11.23.
ChemActivity 17: Electrophilic Addition
Part A: Read Section 4.3, Chapter 8 through Section 8.4A, and Chapter 13 through Section 13.2.
Part B: Read Section 8.5. Do problem 8.35.
Part C: Do problems 8.29a-c, 8.34, and 8.40.
Part D: Read Section 18.3.
ChemActivity 18: Epoxide and Bromonium Ring Opening
Read Sections 8.8 and 13.5. Do problems 8.30a-c.
ChemActivity 19: Carbon-Carbon Bond Formation
Read Chapter 9 through Section 9.3, and 9.5. Do problem 9.15.
ChemActivity 20: Radical Halogenation of Alkanes
Part A: Read Section 19A.
Part B: Read Sections 19.1B-D and 19.2-19.4. (*Note:* **NBS** is a reagent that produces Br radicals. Assume it is equivalent to using Br_2 and light.)
ChemActivity 21: Anti-Markovnikov Addition of HBr
This book does not cover anti-Markovnikov addition of HBr to alkenes. However, this mechanism is similar to the very important radical chain reaction mechanism giving rise to polymers described in Section 19.5B.
ChemActivity 22: Hydroboration-Oxidation
Part A: Read Section 8.6. Do problems 8.29e-i, 8.31a-e, and 8.32.
Part B: Read Sections 8.9 and 13.7.
ChemActivity 23: Electrophilic Addition to Alkynes
Read Section 9.4.
ChemActivity 24: MO Theory/Conjugation/UV-vis
Part A: Read Section 2.10, and Chapter 18 through Section 18.2.
Part B: Read Sections 2.2 and 2.3.
ChemActivity 25: Aromaticity
Do problem 10.29.
ChemActivity 26: NMR of Aromatic Molecules
Read Chapter 10 through Section 10.2. Do problems 10.18 and 10.19.
ChemActivity 27: Polymerization Reactions
Read Sections 8.4B, 19.5A, 21.6. Do problem 21.24.
ChemActivity 28: Diels-Alder Reaction
Read Sections 18.4 and 25.2B. Do problems 18.20 and 18.22.
ChemActivity 29: Electrophilic Aromatic Substitution
Part A: Do problem 10.24.
Part B: Do Problem 10.33.
Part C: Read Section 10.4. Do problems 10.20 and 10.21.
Part D: Read Sections 10.5 and 21.7A. Do problems 10.22, 10.23, and 10.28.
ChemActivity 30: Synthesis Workshop I

Read Sections 4.4, 9.6, 21.1, and 21.3-21.5.

ChemActivity 31: Nucleophilic Addition to a Carbonyl

Part A: Read Chapter 14 through Section 14.3, and Sections 14.5 and 14.6. Do Problems 14.34, 14.35, 14.37, 14.38, and 14.40.

Note: The book's answers use the following reagents that we have not learned: PBr_3 is a more efficient way to change an OH into a Br (we used HBr); chromic acid (CrO_3) oxidizes an OH to a C=O (we used $KMnO_4$).

Part B: Read Sections 14.7-14.9. Do problems 15.33a,b.

ChemActivity 32: Application of NAC: Protecting Groups

Read Section 21.2.

ChemActivity 33: Reactions at the a**-C of Carbonyl Group**

Part A: Read Section 16.4. Do problems 16.22, 16.24, 16.34, and 16.39.

Part B: Read Sections 16.5-16.6, and 17.1-17.2. Do problems 16.25, 16.26, 16.35, and 16.38.

ChemActivity 34: Base Catalyzed Aldol Reactions

Read Sections 17.4A and 17.6A.

ChemActivity 35: Acid Catalyzed Aldol Reactions

ChemActivity 36: a ,b**-Unsaturated Carbonyl Compounds**

Read Section 17.5B.

ChemActivity 37: Michael Additions

Read Sections 17.5A and D.

ChemActivity 38: Acidity of Phenols

Read Sections 16.1A&B.

ChemActivity 39: Nucleophilic Aromatic Substitutions

Read Section 21.7C.

ChemActivity 40: Carboxylic Acids

Part A: Read Chapter 15 through Section 15.3.

Part B: Read Sections 15.5-15.7. Do problems 15.25 and 15.29.

ChemActivity 41: Carboxylic Acid Derivatives

Part A: Do problems 15.45 and 15.47.

Part B: Read Section 15.4. Do problems 15.32 and 15.56.

ChemActivity 42: Claisen Reactions

Part A: Read Section 17.4B.

Part B: Read Section 17.6B. Do problems 17.36.

Part C: Read Section 17.6C.

ChemActivity 43: Decarboxylation

Read Section 17.3. Do problems 17.34.

ChemActivity 44: Synthesis Workshop II

Do problems 14.33, 14.42, 14.43, and 17.36.

ChemActivity 45: Amines and Amino Acids

Part A: Read Sections 16.1C, and 20.1-20.3. Do problems 20.23a,b and 20.31.

Part B: Read Sections16.2 and 20.1. Do problems 16.28, 16.29, and 16.37.

ChemActivity 46: Amino Acids, Peptides, and Proteins

Read Sections 15.8, 21.8, 23.3 and 23.8.

McMurry, *Organic Chemistry*, 5th Edition

ChemActivity 1: Bond Angles and Shape

Part A: Read pages 1-3 in your text, Organic Chemistry by J. McMurry, 5th Edition

Part B: Read Section 1.4 (pp. 7-9)

ChemActivity 2: Lewis Structures

Part A: Read Section 1.5 (pp. 9-12) in you text.

Part B: Read Section 2.3 (pp. 41-44) in your text.

ChemActivity 3: Resonance Structures

Part A: Read Sections 2.4 (pp. 44-45) in your text.

Part B: Read Sections 2.5 and 2.6 (pp. 46-48) in your text. Do Problems 2.36c; 2.55a, b and d; and 2.56.

ChemActivity 4: Conformers of Carbon Structures

Read Sections 4.1 to 4.4 (pp. 111-121) in your text. Do Problems 4.25, 4.26 and 4.27 at the end of Chapter 4 (p. 147). Necessary structures are provided below.

ChemActivity 5: Isomers of Carbon Structures

Part A: Read sections 3.2 through 3.4 in your text (pp. 79-93 of McMurry 5th Ed.). Do the following problems at the end of Chapter 3 in your text: 3.25, 3.26, 3.31, 3.32 and 3.34.

Part B: Read Sections 3.8 (pp. 99 – 101 in McMurry 5th Ed.) and 6.5 (pp. 196 – 197 in McMurry 5th Ed.). Do problems 3.38, 3.42 and 3.46 at the end of Chapter 3.

ChemActivity 6: Potential Energy and Cyclohexane

Part A: Read Sections 4.4-4.6 (pp. 121-124) and Section 4.8 (pp. 1125-127) in your text.

Part B: Read Sections 4.8-4.14 (pp. 127-141) in your text. Do problems 4.37 and 4.43 at the end of Chapter 4.

ChemActivity 7: Chirality

Part A: Read Chapter 9 through Section 9.5 (pp. 306-315) in your text. Do problems 9.35, 9.36, 9.40, 9.41, 9.42a,b at the end of Chapter 9.

Part B: Read Sections 9.6-9.12 (pp. 315-330) in your text. And do problems 9.29, 9.43-9.45, 9.47, 9.50, 9.51, 9.67, 9.69, 9.75, and 9.78 at the end of Chapter 9.

ChemActivity 8: Acid-Base Reactions

Read Sections 2.7 through 2.9 (pp. 50-55) in your text.

ChemActivity 9: The Nucleus and Inductive Effects

Part B: Read Chapter 2 through Section 2.3 (pp. 35- 44). Do problems 2.27, 2.29, 2.30 (get the definition of dipole moment from your reading), and 2.34 for review.

ChemActivity 10: The Resonance Effect

Review Sections 2.4 through 2.6 and read Section 2.10 (pp. 56-57). Do problems 2.35, 2.39, 2.42 (note that Na^+ is always an inert spectator ion and is not involved in the reaction), 2.44, 2.46, 2.48, and 2.60.

ChemActivity 11: Electron Orbitals

Part A: Read Chapter 11 through the end of Section 11.4 (pp. 385-392).

Part B: Read Chapter 1, **paying particular attention to Sections 1.7 through 1.11** (pp. 16-25). Do problems 1.28-1.31, 1.36, and 1.42-1.45.

ChemActivity 12: One-Step Nucleophilic Substitution

Part B: Read Section 11.5 in your text. Do problems 11.26a&c, 11.30a-c, 11.31a,c,d,e, 11.32, 11.36, 11.37, 11.40 and 11.49.

ChemActivity 13: Two-Step Nucleophilic Substitution

Part A; Read Section 6.10 (pp. 212-216) in your text.

Part B: Read Sections 11.6-11.9 (pp. 401-413) in your text. Do problems 11.25, 11.27, 11.28, 11.35, and 11.38 at the end of Chapter 11.

ChemActivity 14: Elimination

Part A: Read Sections 11.14 and 17.7 (an "**E1**" reaction is a 2-step elimination reaction.)

Part B: Read Section 11.15 in your text.

ChemActivity 15: Stereochemistry of E2 Reactions

Part A: Read Chapter 6 through the end of Section 6.7 (pp. 188-206). And Section 11.10 (pp. 413-414).

Part B: Read sections 11.11 through the end of Chapter 11 (pp. 414-431). Do problems 11.24, 11.34a, 11.43, 11.44-11.46, 11.54, and 11.63.

ChemActivity 16: Spectroscopy

Part A: Read Sections 12.5 through the end of Chapter 12 on IR spectroscopy. Do problems 12.17, 12.23, 12.25, 12.28, 12.32, 12.34a-c, 12.36, 12.37a, 12.41a-c and 12.48.

Part B: Read Chapter 13 through the end of Section 13.7. Focus on interpreting a ^{13}C NMR spectrum, not the physics of how the instrument works. Do problems (assume decoupled ^{13}C NMR for each) 13.31, 13.42, 13.52, and 13.55.

Part C: Read Chapter 13, Sections 13.8-13.11. Do problems 13.30, 13.35-13.37, 13.40, 13.41, and for extra practice do problems 13.43-13.50.

ChemActivity 17: Electrophilic Addition

Part A: Read sections 5.4 (p. 156-181) through the end of Chapter 5, Section 6.8 - 6.11 (p. 206-219), and Section 9.15 (p. 336-337) in your text. Do problems 5.23, 5.28 (we assume $\Delta H = \Delta G$), 5.38 at the end of Chapter 5. Do problems 6.37, 6.39, and 6.40 at the end of Chapter 6. Do problem 9.62b at the end of Chapter 9.

Part B: Read Sections 6.12 through the end of Chapter 6 (pp. 219-223). Do Problems 6.46-6.48 at the end of Chapter 6.

Part C: Read Section 7.4 (pp. 239-241) in your text.

Part D: Read Sections 14.5-14.6 (pp. 529-533) in your text.

ChemActivity 18: Epoxide and Bromonium Ring Opening

Read Sections 7.2-7.3 (pp. 234-239) and Section 18.8 (pp. 720-724) in your text. Do problems 7.23a-c, 7.24a-c&e, and 7.48 at the end of Chapter 7.

ChemActivity 19: Carbon-Carbon Bond Formation

Read Section 10.8 (pp.369-371), Sections 8.6 (pp. 283-285) and 8.8-8.10 (pp. 287-296) and Review the chart on pp. 76 & 77. Do problems 8.21, 8.22, 8.28c&d and 10.24e.

ChemActivity 20: Radical Halogenation of Alkanes

Part A: Read Sections 5.1-5.3 and (pp. 151-156) and Section 10.6 (pp. 365-368).

Part B: Read Sections 10.1-10.5 (pp. 355-365) in your text. Do problems 10.2, 10.23a,c&f, 10.31 (Note: **NBS** is a reagent that produces Br radicals. Assume it is equivalent to using Br_2 and light.)

ChemActivity 21: Anti-Markovnikov Addition of HBr

Our book does not cover anti-Markovnikov addition of HBr to alkenes. However, this mechanism is similar to the very important radical chain reaction mechanism giving rise to **polymers**. These reactions are described in Section 7.10 (pp. 256-260). Work through the mechanism of polystyrene (Styrofoam®) from styrene. Necessary structures are shown on p. 258.

ChemActivity 22: Hydroboration-Oxidation

Part A: Read Sections 7.4 and 7.5 (pp. 239-246) in your text. Do problems 7.40 and 7.42a,b&d at the end of Chapter 7.

Part B: Read Section 7.8 (pp. 252-255), the summary of reactions at the end of Chapter 7 (pp. 263-265), Section 17.8 (pp. 679-681) and Section 19.3 (pp. 759-760). Do problems 7.23-7.25 (Note that $Hg(OAc)_2$, H_2O then $NaBH_4$ is equivalent to adding H_3O^+/H_2O, but gives better yields.), 7.26(except part c), 7.27-7.34, 7.37, and 7.39.

ChemActivity 23: Electrophilic Addition to Alkynes

Read all of Chapter 8. Choose from among problems 8.14-8.39 (except 8.32) at the end of Chapter 8 for extra practice. Particularly useful are the synthesis problems 8.16, 8.31, 8.33, 8.34, 8.35a,c, 8.36 and 8.38.

ChemActivity 24: MO Theory/Conjugation/UV-vis

Part A: Read Section 14.1, 14.2 and 14.4, and review Sections 14.5-14.6 (which were covered in CA 17D). Do problems 14.20-14.23 except 14.21e (Note for 14.23: we will learn about UV-vis spectroscopy in the next activity).

Part B: Read Sections 14.3 and 14.10-14.13. Do problem 14.43.

ChemActivity 25: Aromaticity

Part A: Read Chapter 15 through the end of Section 15.3. Do problems 15.17-15.20, 15.24-15.26, and 15.31-15.32.

Part B: Read Sections 15.4-15.9 in your text. Do problems 15.33, 15.37 and 15.40.

ChemActivity 26: NMR of Aromatic Molecules

Read Section 15.10 in your text and do problems 15.43 and 15.44. Note the position of two groups on a benzene ring causes characteristic IR absorptions as follows: *ortho* (735-770 cm^{-1}), *meta* (690-710 cm^{-1}), *para* (810-840 cm^{-1}) For extra practice review problems 13.30-13.31, 13.35-13.37, 13.40-13.50, 13.52, 13.55.

ChemActivity 27: Polymerization Reactions

Read Sections 7.10 and 14.7 and do problem 14.28. Do problems 7.23, 7.24 (except d) 7.25 (except d), 7.26 (except c), 7.27-7.29 and 7.42a-d as review.

ChemActivity 28: Diels-Alder Reaction

Read Sections 14.8 and 14.9 and do problems 14.31, 14.34, 14.35, 14.37, 14.39, and 14.41.

ChemActivity 29: Electrophilic Aromatic Substitution

Part A: Read Sections 16.1-16.4 and

Part B: Do problems 16.28a-b (halogens are electron withdrawing groups), 16.36, 16.39 and 16.43.

Part C: Read Sections 16.5 and 16.6 in your text.

Part D: Read Section 16.7 in your text and do problems16.27, 16.29-16.32, 16.35, 16.37, and 16.40-16.42.

ChemActivity 30: Synthesis Workshop I

Read Sections 16.7 and 16.10-16.12 and do problems 16.47c-d, 16.48b-d, 16.49a&c, 16.50a&c, and 16.51.

ChemActivity 31: Nucleophilic Addition to a Carbonyl

Part A: Read Chapter 19 through Section 19.8. Do problems 19.34, 19.42 and 19.43. Note: the book's answers use the following reagents that we have not learned: PBr_3 is a more efficient way to change an OH into a Br (we used HBr); chromic acid (CrO_3) oxidizes an OH to a C=O (we used $KMnO_4$). For nomenclature practice do problems 19.25-19.27

Part B: Read Section 19.9 and do problems 19.29-30a,d,e&h; 19.36 and 19.38a,b.

ChemActivity 32: Application of NAC: Protecting Groups

Read Section 19.11 in your text and do problem 19.37.

ChemActivity 33: Reactions at the a-C of Carbonyl Group

Part A: Read Section 22.5-22.8 (through the end of page 917). Do problems 22.20-22.24.

Part B: Read Sections 22.1-22.3 and do problem 22.42c,e&f.

ChemActivity 34: Base Catalyzed Aldol Reactions

Part A: Read Sections 23.1-23.3 in your text and do problem 23.25a,e&f.

Part B: Do problems 23.25c,b&d and 23.35b-d.

Part C: Read Sections 23.24-23.27 in your text and do problems 23.26, 23.28-23.30, 23.32, and 23.33.

ChemActivity 35: Acid Catalyzed Aldol Reactions

Read Section 23.14 in your text

ChemActivity 36: a ,b-Unsaturated Carbonyl Compounds

Part A: Read Sections 19.14-19.15 in your text and do problem 19.28.

Part B: Do problem 19.39(except a&g).

ChemActivity 37: Michael Additions

Read Section 23.11 in your text.

ChemActivity 38: Acidity of Phenols

Part A: Do problems 17.24a-e, 17.27, 17.29, 17.31, and 17.33

Part B: Read Section 17.3 in your text. Do problems 17.41, 17.49, and 17.52. Review NMR and do problems 17.54-17.62. Recall that a deuterium (D) does not show up on an NMR spectrum. Addition of D_2O to a compound replaces all H's with pKa < 14 with a D.

ChemActivity 39: Nucleophilic Aromatic Substitutions

Read Section 16.8.

ChemActivity 40: Carboxylic Acids

Part A: Read Chapter 20. Do problems 20.17-20.21, 20.22a-d, 20.23, 20.24, 20.28-20.31 and 20.38.

Part B: Read Chapter 21, Sections 21.1 and 21.6-21.8. Do NMR problems 20.47, 20.48 at the end of Chapter 20, and problems 21.35, 21.36, 21.40, 21.42a-g, 21.45, 21.48 and 21.56

ChemActivity 41: Carboxylic Acid Derivatives

Part A: Read Sections 21.2-21.4 and do problems 21.41, 21.43, and 21.44.

Part B: Read Section 21.5 and do problems 21.51, 21.52b-d, 21.57 (an aromatic NO_2 can be oxidized to an aromatic NH_2 without effecting an aromatic ester group), and 21.58.

ChemActivity 42: Claisen Reactions

Part A: Read Sections 23.8 and 23.10. Do problem 23.40 as a review of Michael reactions.

Part B: Read Section 23.9. Do problems 23.36 and 23.37.

Part C: Review all of Chapter 23 except Section 23.12.

ChemActivity 43: Decarboxylation

Read Section 22.8 in your text. Do problems 22.26a, 22.35, 22.36, and 22.38.

ChemActivity 44: Synthesis Workshop II

Review Section 22.8 in your text and do problems 22.27-22.30.

ChemActivity 45: Amines and Amino Acids

Part A: Read Chapter 24 through the end of Section 24.5. Do problems 24.23-24.25, and 24.38-24.40.

Part B: Read Sections 24.6 and 24.7. Do problems 24.28a,b,d,e; 24.29d,e; 24.30a,c,e,f; and 24.33(except d).

Brown & Foote, *Organic Chemistry*, 3rd Edition

ChemActivity 24: MO Theory/Conjugation/UV-vis

Part A: Read section 23.1 and review section 23.2 (which we covered in CA 17D). Do problems 23.11 - 23.13 (23.14 - 23.20 for extra review).

Part B: Review section 1.8 and read 23.5. Do problems 23.44, 23.45.

ChemActivity 25: Aromaticity

Part A: Read sections 20.1, 20.3 and do problems 20.8, 20.12, 20.14.

Part B: Read section 20.2 and do problems 20.15, 20.16, 20.17.

Mass Spectrometry

Read all of chapter 14 and do problems 14.4, 14.8, 14.26, 14.29

ChemActivity 26: NMR of Aromatic Molecules

Read section 20.4 and do problems 20.20, 20.21, 20.22. Note the position of two groups on a benzene ring causes characteristic IR absorption as follows: *ortho* (735 – 770 cm^{-1}), *meta* (690 – 710 cm^{-1}), and *para* (810 – 840 cm^{-1}). For extra practice review text chapter 13.

ChemActivity 27: Polymerization Reactions

Read sections 24.1 the architecture of polymers, 24.2 polymer notation and nomenclature, 24.5 step-growth polymerizations, 24.6A radical chain-growth polymerizations , 26.4 steroids. Do problems 24.9, 24.12, 24.13.

ChemActivity 28: Diels – Alder Reaction

Read section 23.3 the Diels – Alder reaction and do problems 23.21, 23.22, 23.24, 23.29, 23.33.

ChemActivity 29: Electrophilic Aromatic Substitution

Part A: Read sections 21.1 Electrophilic Aromatic Substitution and 4.5 Lewis Acids and Bases. Do problem 21.7

Part B: Read section 21.2 Disubstitution and Polysubstitution and do problems 21.14, 21.15, 21.19

Part C: Do problems 21.20, 21.21

Part D: Do problems 21.23, 21.38, 21.42

ChemActivity 30: Synthesis Workshop I

Read Interchapter Medicinal Chemistry – Problems in Organic Synthesis

Try these challenging problems: MC.8 c, e, MC.17, MC.47

ChemActivity 31: Nucleophilic Addition to a Carbonyl

Part A: Read sections 16.1-16.9 Aldehydes and Ketones (Skip Wittig reaction for now). Do problems 16.17, 16.18, 16.20, 16.31, 16.32.

Part B: Read section 16.10 (Addition of nitrogen nucleophiles). Do problems 16.43, 16.44.

Chemactivity 32: Application of NAC: Protecting Groups

Review section 16.8 (Addition of oxygen nucleophiles), do problems 16. 32, 16.33.

Chemactivity 33: Reactions at the a-C of Carbonyl Groups

Parts A & B: Read sections 16.11, 16.12 (Keto-enol tautomerism, Reactions at α-C). Do problems 16.46, 16.50, 16.51, 16.52.

ChemActivity 34: Base Catalyzed Aldol Reactions

Parts A, B, C: Read sections 19.1, 19.2 Aldol Reaction, Directed Aldol Reaction. Do problems 19.18, 19.19, 19.22.

ChemActivity 35: Acid Catalyzed Aldol Reactions

Read section 19.4 (Claisen and Aldol Condensations in the Biological World), do problem 19.44.

ChemActivity 36: a , b-Unsaturated Carbonyl Compounds

Parts A & B: Read section 19.8 (Conjugate Addition to α, β-Unsaturated Carbonyl Compounds). Do problems 19.51 (formation of intermediate C involves a Dieckmann Condensation which you will need to look up!), 19.52, 19.53.

ChemActivity 37: Michael Additions

Do problems 19.55, 19.60, 19.61b.

ChemActivity 38: Acidity of Phenols

Read section 20.5 in text (Phenols). Do problems 20.32, 20.35, 20.36, 20.40.

ChemActivity 39: Nucleophilic Aromatic Substitution

Read section 21.3 in text (same title), do problems 21.28, 21.29.

ChemActivity 40: Reactions of Carboxylic Acids

Read Chapter 17 through 17.7 in text and Figure 18.2

Part A: Do problems 17.7, 17.13, 17.17 a, b, c, d, 17.18d, 17.19, 17.29, 17.31

Part B: Do problems 17.35, 17.36, 17.37

ChemActivity 41: Reactions of Acid Chlorides and Anhydrides

Read section 17.8 and Chapter 18

Part A: Do problems 18.17, 18.20, 18.22, 18.23

Part B: Do problems 18.28, 18.29, 18.32, 18.46

ChemActivity 42: Claisen Reactions

Parts A, B, C: Read sections 19.3, then review all of Chapter 19 except 19.6, 19.7. Do problems 19.31, 19.32, 19.40, 19.58, 19.59a.

ChemActivity 43: Decarboxylation

Read sections 17.9, do problems 17.40, 17.41, 17.43.

ChemActivity 44: Synthesis Workshop II

Read sections 19.6, 19.7. Do problems 19.46, 19.49, 19.50.

ChemActivity 45: Amines and Amino Acids

Read chapter 22. Do problems 22.18, 22.19, 22.21, 22.24, 22.29.

ChemActivity 46: Amino Acids and Peptides

Read chapter 27.

Vollhardt & Schore, *Organic Chemistry*, 3rd Edition

ChemActivity 6: Potential Energy and Cyclohexane
Read Sections 4-3 to 4-7.
ChemActivity 7: Chirality
Read Chapter 5 through Section 5-6. Do problems 25, 28, 29, 31, 33, and 57 (Ch 5).
ChemActivity 10: The Resonance Effect
Read Section 2-9
ChemActivity 11: Electron Orbitals
Read Sections 1-6 to 1-8
ChemActivity 12: One-Step Nucleophilic Substitution
Reach Chapter 6. Do problems 30, 33b-d, 36a,c,d, 37 and 41 (Ch 6).
ChemActivity 13: Two-Step Nucleophilic Substitution
Read Chapter 7 through Section 7-5. Do problems 18, 20, 22, and 24.
ChemActivity 14: Elimination
Read Sections 7-6 to 7-9. Do problems 26 and 32.
ChemActivity 16: Spectroscopy
Read Chapter 10. Do problems 22, 23, 26, and 30 (Ch 10); Read Section 11-5. Do problem 26 (in Ch 11).
ChemActivity 17: Electrophilic Addition
Part A: Read Chapter 12 through Section 12-4. Do problems 28, 30a, and 33e.
Part B: Read Sections 12-5 and 12-6.
Part D: Read Sections 14-6.
ChemActivity 20: Radical Halogenation of Alkanes
Read Sections 3-4 to 3-9. Do problems 18-21.
ChemActivity 21: Anti-Markovnikov Addition of HBr
Read Section 12-12. Do problems 25a-c, 28, 30a,c,d,f, 31a-d, and 32a.
ChemActivity 22: Hydroboration-Oxidation
Read Sections 12-8 to 12-11. Do problems 45 and 46.
ChemActivity 23: Electrophilic Addition to Alkynes
Read Chapter 13 (except Sections 13-3 and 13-10). Do problems 29a,b,e, 38a,f-j, and 40.
ChemActivity 25: Aromaticity
Read Sections 15-2, 15-3, 15-7 and 15-8. Do problems 36 and 37 (Ch 15). Read Chapter 14 through Section 14-7.
ChemActivity 26: NMR of Aromatic Molecules
Read Chapter 15 through Section 15-6 (Sections 15-2 and 15-3 are review).
ChemActivity 27: Polymerization Reactions
Read Sections 12-13 to 12-16, and Section 14.8.
ChemActivity 29: Electrophilic Aromatic Substitution
Part A: Read Sections 15-9 to 15-14.
Part B: Read Chapter 16 through Section 16-4. Do problems 25, 27, 29, 32a-d, 33 and 34.
Part C: Read Sections 16-5. Do problems 35d,g, and 37.
ChemActivity 31: Nucleophilic Addition to a Carbonyl
Read Section 20-2. Read Chapter 17 through Section 17-11 (excluding 17-10; 17-1 to 17-4 are review.

ChemActivity 32: Application of NAC: Protecting Groups
Read Sections 17-8, 17-12 and 17-13. Do problems 17a-g, 33a,b,d, 41 and 42a,b.

ChemActivity 33: Reactions at the a-C of Carbonyl Group
Read Chapter 18 through Section 18-4. Do problems 26a,b,e, 27a,b,e, 28a,b,e, and 29.

ChemActivity 34: Base Catalyzed Aldol Reactions
Read Sections 18-5 to 18-7. Do problems 36c, 37c, 38 and 40.

ChemActivity 36: a,b-**Unsaturated Carbonyl Compounds**
Read Sections 18-9 to 18-12. Do problems 44a-e, 46a,b, 47a,b, 49, 50a (UV data tells you it is an aldehyde or ketone), and 50c (UV data tells you it is an alkene).

ChemActivity 38: Acidity of Phenols
Read Section 22-3. Do problem 42.

ChemActivity 39: Nucleophilic Aromatic Substitutions
Read Section 22-4. Do problems 34a, 36b, 37 and 43d.

ChemActivity 40: Carboxylic Acids
Read Chapter 19 (excluding Sections 19-8, 19-12, and 19-13). Do problems 18a-d,g,i, 20a-c,e, 24a-d, and 44. Read Sections 20-4, 20-6, and 20-8.

ChemActivity 41: Carboxylic Acid Derivatives
Read Sections 19-8 and 19-13. Read Chapter 20 through Section 20-5 (excluding 20-4). Do problems 31i-e, 34a,b, and 36 (Ch 20).

ChemActivity 42: Claisen Reactions
Read Section 23-1. Do problems 22-24.

ChemActivity 43: Decarboxylation
Read Section 23-2 and 23-3. Do problems 26-28 and 30b.

ChemActivity 45: Amines and Amino Acids
Read Chapter 21 through Section 21-7.

ChemActivity 46: Amino Acids, Polypeptides and Proteins
Read Sections 26-1, 26-4 and 26-8.

Section 3: Guide to Individual ChemActivities

(Key New Concepts, Instructor's Notes, Sample Quizzes)

The following pages provide a description and helpful information for each ChemActivity. You may find it useful to read this information as part of your preparation for class, particularly if this is your first time using the materials.

You will find the following sections listed for each ChemActivity:

Key New Concepts

A bulleted list of the new concepts introduced in that activity.

Instructor's Notes

This section may include:

- Description of how the activity fits into the course as a whole
- Consequences of skipping the activity in terms of subsequent activities
- Explanation of terms, Models or analogies used
- Justification behind nonstandard treatments
- Suggestions on timing, such as where to end class
- Sticking points where students typically have trouble
- Opportunities to challenge fast groups or high achieving groups
- Good places for instructor-led interjections or discussions
- Other implementation suggestions

Sample Quiz

A sample quiz is provided for each Part of each ChemActivity. I have used most of these quizzes at least once, but not all have been carefully checked for validity. You are welcome to use these quizzes in your first year, or it may be more valuable to make them available each day to students as a practice quiz. My quizzes tend to be on the long side; you may find you want much shorter, one-question quizzes, so as to devote maximum class time to group work. The sample quizzes were scored from 0-5 points, with no partial points.

ChemActivity 1: Bond Angles and Shape

Key New Concepts

- Working with peers, rather than competing with them
- Learning by teaching
- Coulombic force
- Planetary model of the atom
- Shared electron pair model of covalent bonding
- Maximally spread out electron pair model for bond angles and shapes

Notes to the Instructor

It may be useful to give a short speech about guided inquiry pedagogy for the purpose of showing your enthusiasm and investment. However, just as lecturing your students on organic chemistry may not be terribly effective, it would be a waste of time for you to spend more than five minutes telling them about guided inquiry. I mostly stick to facts about course structure, and let them discover the efficacy of the method for themselves.

Important facts include: they will be working in groups, how the groups will be assigned, there will be a quiz each day, and exams and quizzes will be taken individually. I emphasize that they are not in competition with each other, and that the single most powerful predictor of success in this course is whether they use a study partner/group outside of class. Basically, students who work completely alone, tend to fail more often. To encourage collaboration, I strongly suggest that you use a grading strategy that at least de-emphasizes the fact that they are being compared with one other. I suggest an absolute grading scale (90-100 = A etc.). If I write a doozie of a test and everyone bombs it, rather than curving, I give a makeup take-home group exam worth 10 points and add the two scores together. The result is similar to curving, without the negative connotations of direct competition. (For more on this, see the section entitled Quizzes, Exams and Grading found in Section 1 of this manual.)

If you are trying this out with big question marks in your mind, do not let on. They are very nervous about this course. They want to see confidence from you, and they DO NOT want you experimenting with their lives. Also, you don't need to put down traditional teaching methods. Regardless of how you feel about lecture, it is what they are familiar with. They still think of lecture as the tried and true way to teach chemistry, so be gentle with them at the beginning.

Finally, let the materials guide you but don't sit on your hands when it comes to answering student questions and getting involved in discussions. Don't sit back and "let the materials do their thing." Frustration is part of learning, but keep the levels low at first while they get used to their new learning environment. Do not refuse to answer questions and tell them it is for their own good that you are making them figure it out for themselves. This will paint you in an adversarial role. The materials are a guide for getting students to think more and interact more, and this will only work if you are all on the same team.

Much of the material in this activity will be review, however, and because of this, students may rush through, relying on facts memorized from previous courses. Try to get them to think about the models. For advanced students, ask them to predict the shape of a center with six atoms bound to it (e.g. SF_6).

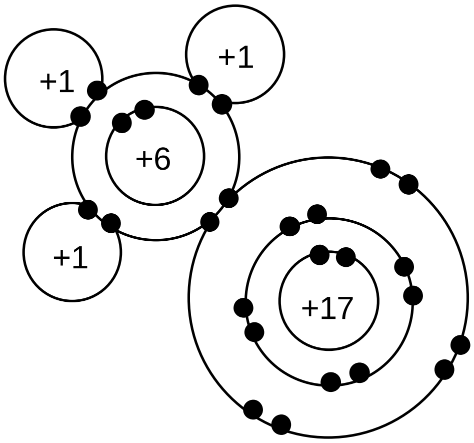
Usually, the only sticking point in this activity is the specification that shape is defined by the positions of the atoms bound, not the lone pairs. A few students are confused by the fact that the non-bonded electrons must be considered since they affect the positions of those atoms.

Quiz 1A

Consider the **valence shell representation** shown below.

a) Draw a **line-bond representation** of this molecule in the box provided.

b) Circle the most likely ∠HXH bond angle among the three choices provided.



a)

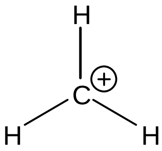
line-bond rep.

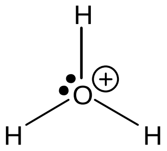
b) HXH bond angle is most likely (circle one)
A. 120^o
B. 106^o
C. 113^o

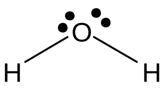
c) Which reasoning best explains why the ∠HXH bond angle is NOT 109.5^o?
A. Four atoms always spread themselves out equally around the central atom.
B. The large atom, with its many lone pairs, takes up a larger space around the central atom than a hydrogen.

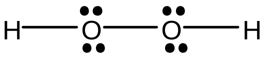
Quiz 1B

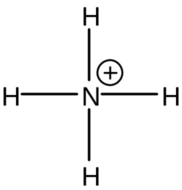
1. Circle each of the following species that is planer.
   Planer = a model could be made with all the atoms in a single plane.











2. Use the shape names you memorized in ChemActivity 1 to describe the shape of each central atom above. (Write the name below each central atom.)

ChemActivity 2: Lewis Structures

Key New Concepts

- Lewis Structures including the octet rule and its corollary for H and He
- Relationship of the octet rule to the number of electrons in a “shell”
- Lewis structures of ions
- Multiple bonds
- Formal charge

Notes to the Instructor

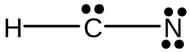
Part A of this activity will be completely review for most students, but it is so important that it is well worth a full class period to make sure that everyone is comfortable with Lewis structures.

Part B is frustrating for some students, particularly since they look around and see that many of their classmates are breezing through it. The ability to quickly “see” formal charges needs to be developed and reinforced at this stage, especially in weaker students. This skill will give them confidence going forward with structures and reactions. A bit of memorization can help with this. Chemists do not stop to calculate everyday formal charges on C, N, O, and halogens. At the end of class, direct students’ attention to the chart in the Exercises for Part B. This exercise asks them to memorize that an oxygen with two bonds (and an octet) has a zero formal charge, with 1 bond it has a negative one formal charge, with 3 bonds it has a +1 etc..

Quiz 2A

- Briefly explain why each structure below is NOT a legitimate Lewis structure.
- Then, draw a legitimate Lewis structure of a neutral molecule with the same molecular formula as each structure shown.

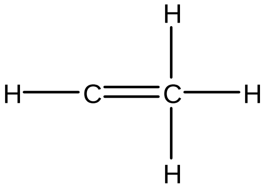
a.



explanation

legitimate Lewis structure iwth formula CHN

b.

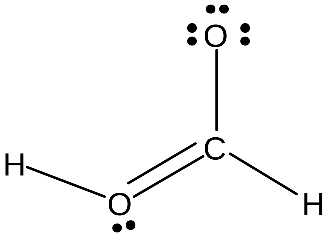


explanation

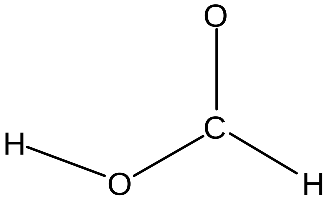
legitimate Lewis structure with formula C_2H_4

Quiz 2B

1. Add the missing formal charges to the Lewis structure of HOCHO below, **LEFT**.
2. There is a better Lewis structure for this arrangement of atoms, draw it using the skeleton below, **RIGHT** (Always include only non-zero formal charges in a Lewis structure).



add the missing formal charges



complete a better Lewis structure

3. Predict what value the ∠HOC bond angle is closest to...
   - A) 180°
   - B) 120°
   - C) 109.5°
   - D) 90°

ChemActivity 3: Resonance Structures

Key New Concepts

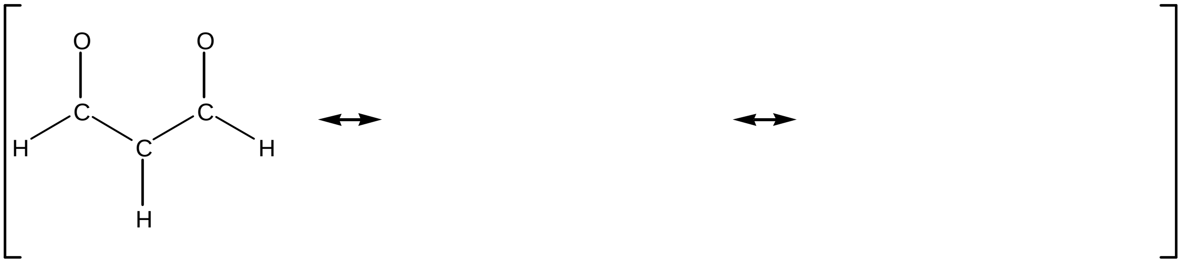
- Resonance structures
- Hybrid structures
- Partial bonds and charges
- Curved arrow notation for generating a set of resonance structures
- Curved arrow notation for representing simple acid-base reactions

Notes to the Instructor

Even though this activity is about resonance structures, it really revolves around learning to use curved arrows. Most students grasp the concept of resonance, but developing facility at seeing alternate resonance structures is another story. An algorithmic way into this is to practice generating resonance structures using curved arrow notation. They will be asked to do this in Part B. Their arrows will be every which way at first. I take the extra time to correct their curved arrow use and let them know that it is a very worthwhile investment.

Quiz 3A

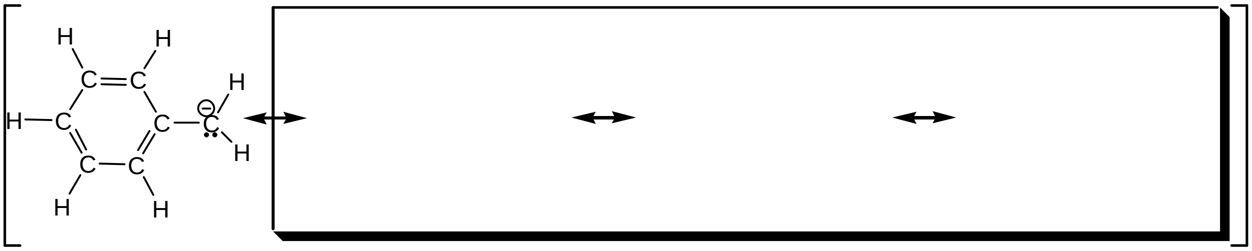
1. A partial structure of the ion $C_3H_3O_2^-$ is given below. Complete a Lewis representation of this ion using the backbone provided.
2. Draw the other two important resonance structures.



The ∠CCC bond angle of this ion is between 120° and 109.5°. Do you expect the ∠CCC bond angle to be **closer to 120°** or **closer to 109.5°** [circle one].

Quiz 3B

One resonance structure of an ion is given below. Use curved arrows to generate the other three important resonance structures and draw them in the boxes provided.



ChemActivity 4: Conformers of Carbon Structures

Key New Concepts

- Single bond rotation
- Chemical potential energy vs. gravitational potential energy
- Potential energy and reactivity
- Steric repulsion
- Newman projections

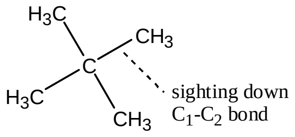
Notes to the Instructor

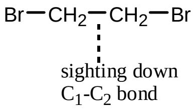
Newman projections cause students fits until they explore them while holding a model. It is often necessary to coach students through the act of closing one eye and holding the end of the model up to their open eye. You may be frustrated that most models do not depict steric interactions, but wide-open models are much better for figuring out Newman projections. You could bring in some space filling models to reinforce the steric barriers to single bond rotation, but I have found that most students do not need much help figuring out steric hindrance. Potential energy is just quickly introduced in this activity, and students will get a chance to develop their understanding further in ChemActivity 6: Cyclohexane.

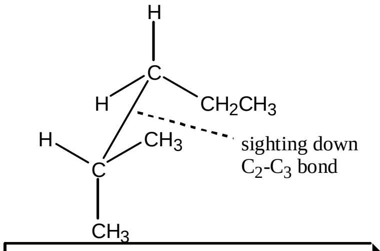
Quiz 4

a) For two of the following molecules draw a Newman Projection of the lowest potential energy conformation sighting down the bond indicated.
Note that **staggered conformations are always lower in potential energy than eclipsed conformations**.

b) On your third Newman Projection label the methyl groups attached to C_2 **anti** or **gauche**.







ChemActivity 5: Isomers

Key New Concepts

- Skeletal structures and visualizing hydrogens
- Constitutional isomers
- Difference between isomers and conformers (criterion for identicalness)
- Stereoisomers (though chirality is not introduced until CA 7)
- Connectivity = the property stereoisomers have in common that constitutional isomers do not
- Cis/trans stereoisomers in alkenes. Don't make the mistake of assuming they will get this without playing with a model

Notes to the Instructor

Students are wrestling with the difference between conformers and isomers. This distinction can be clarified by highlighting the criterion for sameness. The one I use is "Two molecules are the same if models of the two can be superimposed without breaking any bonds."

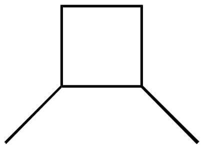
It may be useful to point out the following some time during ChemActivity 5: By the above definition, conformers are actually isomers at very low temperature, when single bond rotation has ceased. For advanced students you might point out examples of molecules with moderate or extreme hindrance to single bond rotation. By showing them there is no sharp line between conformers and isomers you emphasize the importance of always having a physical picture in mind rather than relying on memorized definitions. Some textbooks state that conformers are a type of isomer or stereoisomer and I find this confusing without the above discussion.

To my surprise, some very bright students at first do not see the difference between *cis* and *trans* alkenes. Models help, but I find it is worth it to repeat this seemingly obvious distinction on the board and with models.

Some students may notice there are two different kinds of *trans*-dimethylcyclobutane. I generally acknowledge this fact with a *sinister* smile and leave them to discover chirality in ChemActivity 7.

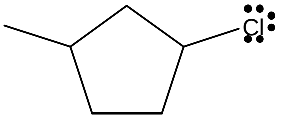
Very fast groups are usually rushing through the material without thinking carefully. It can be useful to slow down these groups by posing advanced questions. The following is a good question for Part B:

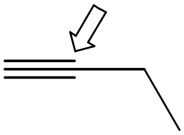
Supplement to CTQ 14: The skeletal representation of methylcyclobutane on the far left of Figure 3a conveys all the information need to make a model. However, the drawing below does not give enough information to make a model. Explain the difference.



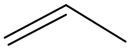
Quiz 5A

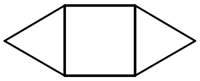
1. Write the name of **two** of the four structures below.





Note: there is a C atom here! No
bend is shown at this C because it is
a 180^o bond angle.



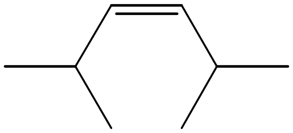


2. For **each** of the skeletal structures above:
   a) Write the molecular formula.
   b) Draw a skeletal representation of a **constitutional isomer** of the structure shown.

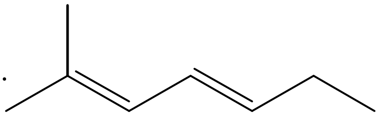
Quiz 5B

1. Draw a stereoisomer of each structure (A-C) shown below.
2. Write the name of Structure A, and the name of its stereoisomer (which you drew).

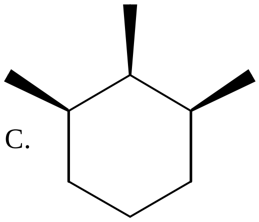
A.



B.



C.



hint: C has more than
one stereoisomer
(just draw one of them)

ChemActivity 6: Cyclohexane

Key New Concepts

- Breaking bonds requires input of energy = positive energy = up arrow on an energy diagram
- Making bonds releases energy = negative energy = down arrow on an energy diagram
- Energy diagrams: Activation energy, Heat of reaction, Exothermic vs. endothermic
- Ring strain
- Chair conformation of cyclohexane and consequences of a ring flip
- Axial vs. equatorial positions (larger groups prefer equatorial positions)
- *Cis* vs. *trans* stereoisomers revisited

Notes to the Instructor

Most introductory students imagine that "energy is stored in bonds" and that when you disturb a high energy molecule like nitroglycerin the atoms fly apart releasing this stored energy…BOOM! What they are missing is that formation of strong bonds in CO_2 and water are the real source of all that released energy. I struggle to get this across, but usually resort to asking them to memorize that breaking bonds requires energy and making bonds releases energy. One year I tried to use magnets to demonstrate that two objects that are attracted to one another could do work, but they were not very impressed. Since then I have relied on the fact that they generally remember that breaking bonds requires energy (which is easily reinforced by straining to pull apart a model), and I ask them to memorize that the opposite is also true. I have had success with the slot machine analogy for setting up sign conventions for reaction energies. I use this analogy extensively in ChemActivity 8, where pKa's are used to quantify energy changes in acid-base reactions.

Regarding cyclohexane conformations, MODELS ARE IMPARATIVE. I find that models are also needed to convey the difference between cis and trans di-substituted rings.

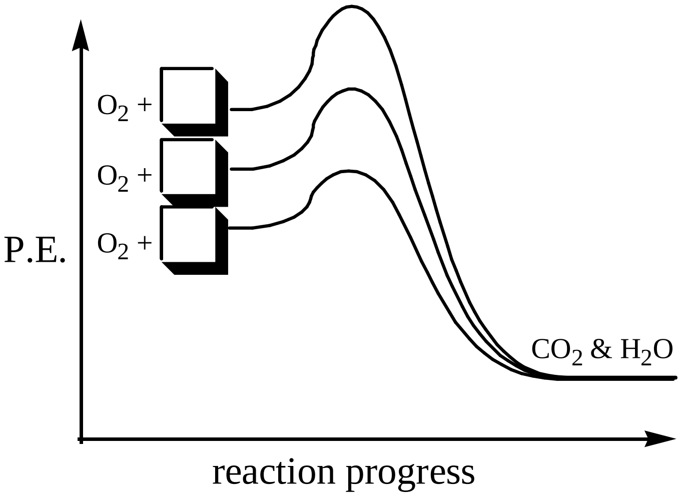
Quiz 6A

A.

B.

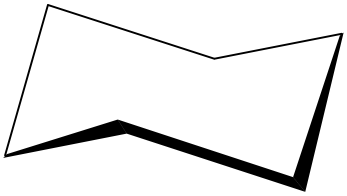
C.

1. Draw skeletal representations of each of the following molecules in the boxes above. Use wedge and dashes as needed: **A = cyclohexane**; **B = *trans*-1,2-dimethylcyclobutane**; **C = *cis*-1,2-dimethylcyclobutane**.
2. Place the letters A, B and C, as appropriate, in the boxes on the energy diagram below.
3. Add to the energy diagram a **heat of reaction** arrow for the burning of the molecule you think is the **best fuel**. (Best fuel = "**releases the most heat per kg burned**.")
4. Are these reactions **exothermic** or **endothermic**? [circle one]
5. Is ΔH_{rxn} for each **positive** or **negative**? [circle one]

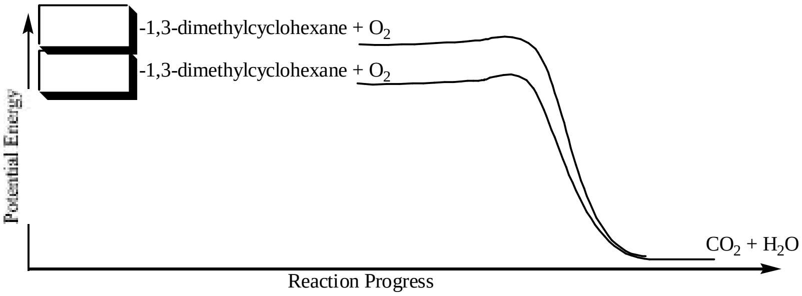


Quiz 6B

1. Complete the following chair representation of ***cis*-1,3-dimethylcyclohexane**. Show the molecule in its **lowest potential energy conformation**. (The backbone is drawn for you-add H's and CH_3's.)



2. Complete the energy diagram by writing the word "***cis***" in one box and "***trans***" in the other box.



ChemActivity 7: Chirality

Key New Concepts

- Chirality (enantiomers, diasteriomers, racemic mixture)
- External mirror plane
- Internal mirror plane (plane of symmetry)
- Chiral center
- Assigning absolute configuration (R and S)
- Meso compounds

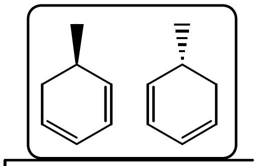
Notes to the Instructor

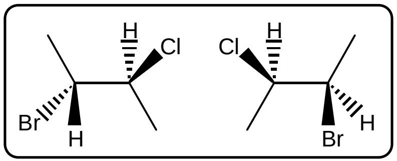
Without models, it is nearly impossible to even convince most students that there are two unique ways to arrange four different groups around a tetrahedral carbon. Models are needed for most students to find internal mirror planes, and are a great help in the initial assignment of R and S. One concept that is missing from this activity is the idea that R and S molecules are really VERY different from one another, that is, chirality matters. I like to reinforce this by making every student shake the LEFT hand of their neighbor using their RIGHT hand. This experience is so different from the familiar feeling of shaking hands the normal way (right to right), that it helps them remember that handedness matters. This can be a lead-in to discussion of chiral drugs for which one enantiomer is active at a binding site and the other is inactive (such as ibuprofen) or deleterious (such as thalidomide).

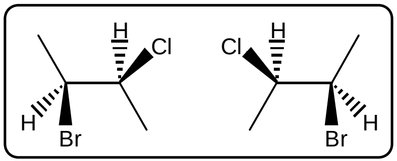
Quiz 7A

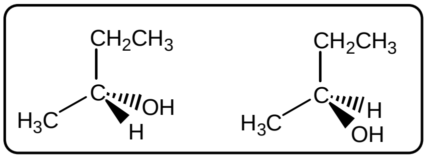
1. Under each pair, write the term that best describes the relationship between them. Some terms may be used more than once, some terms may not be used at all. Choose from:

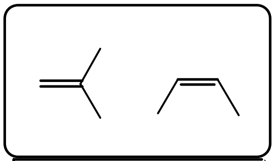
identical **enantiomers** **constitutional isomers** **diasteriomers**

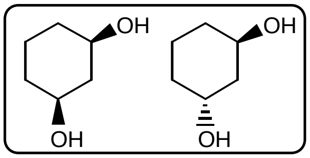










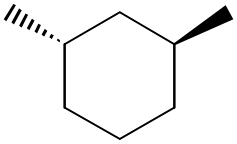


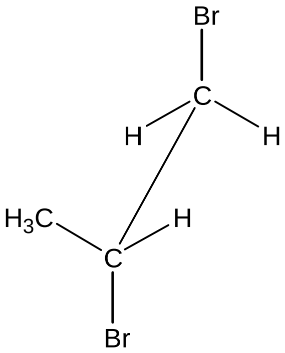
2. Circle each molecule above that is **NOT CHIRAL** (achiral).

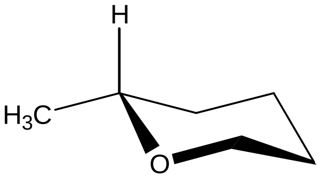
BONUS: Write a correct name above any one achiral structure appearing on this quiz.

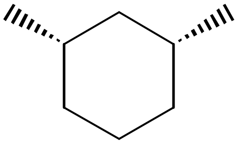
Quiz 7B

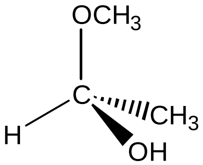
1. Mark each **chiral center** below with an *.
2. Determine the absolute configuration of each chiral center and **label it with an R or S**.











BONUS: Write the name of the one species above that is not chiral.

ChemActivity 8: Acid-Base Reactions

Key New Concepts

- Acid-Base conjugate pairs
- pKa as an estimate of the energy change in an acid dissociation
- pKa as an estimate of bond strength in acids
- pKa as an estimate of the potential energy of a conjugate base
- The “charge effect” = negative species are generally higher in energy than neutral or positive species
- Estimating equilibrium positions from pKa data
- For simplicity, the pKa of a strong acid should be assumed to be zero

Notes to the Instructor

You may have more trouble with this activity than some of your students because of the unconventional treatment of pKa’s. In particular it may seem strange at first to use pKa’s as an estimate of the energy required for heterolytic cleavage of an H—A bond. For the mathematical basis of this assertion, please see Exercise 7 of this activity. This treatment will be carried over into the activities on nucleophilic substitution and elimination where pKa’s will be used to estimate the energy required for heterolytic C—X bond cleavage, and to estimate the energy of X^{-} species acting as nucleophiles or leaving groups.

To my knowledge, this treatment of pKa's is not found in any textbooks, but it makes sense to students. There are several advantages to this: it sidesteps log math, it emphasizes the fact that breaking bonds requires energy and making bonds releases energy, it emphasizes the fact that pKa's describe a process, not an acid, and it attaches this process to a visual, graphical representation that reinforces the conventions of energy diagrams (up is positive, energy in; down is negative, energy out).

Most students who are exposed to a traditional treatment of pKa successfully memorize that the lower the pKa of an acid, the stronger that acid, but some have trouble with the idea that the higher the pKa, the stronger the conjugate base. In any case, they don't have a picture in their head attached to these memorized facts. The Model used here attaches a picture to the concept of pKa, allowing students to visualize that the less energy it takes to pull off the proton (lower pKa), the stronger the acid; and the more energy you get back when you feed a base a proton (higher pKa), the stronger the base.

You may want to verify the math and derivation for yourself, but I have found that it does little for students unless they are math whizzes.

There are several assumptions being made here:

1) The energy of a molecule is inherent in its electrons so when you put energy into an acid to liberate the proton, all of this energy goes into the new pair of electrons on the conjugate base.

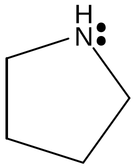
2) pKa's are based on aqueous chemistry so they are only estimates when dealing with pKa's outside of 0-16 and when dealing with non-aqueous solvents.

3) ΔS can be neglected for most organic reactions. This allows us to use ΔH as a measure of spontaneity and equilibrium position.

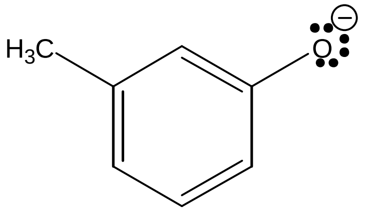
4) Any pKa less than zero should simply be rounded to zero. I have found this much easier than making them deal with the negative pKa's. For example, students have trouble with the idea that it takes negative energy to break a bond on HCl, especially after we have told them that breaking bonds ALWAYS requires input of energy. Later, once they have mastered this, they are primed to learn about solvent effects, and that non-covalent bonds to solvent explain the negative pKa's of the strong acids. But even with solvent effects you really have to dig deep into the math to explain why the pKa of hydronium ion is -1.7 instead of zero (it comes from the fact that pKa's are based on K_a's instead of K_{eq}'s. Note that -log 55 = -1.7). The bottom line: I suggest you have them assume that the definition of a strong acid is that it takes about zero pKa units of energy to liberate the proton—essentially assuming that the pKa of any strong acid is zero. The pKa's are estimates anyway and I think it is more important to get across the concepts of bond making and breaking than to have rigorous quantitative answers.

Quiz 8

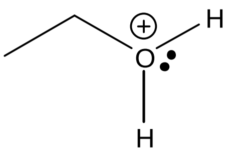
Rank the species below from **lowest** (= **1)** to highest potential energy. If you think two species have the same potential energy, give these two species the same number.



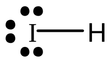
rank =



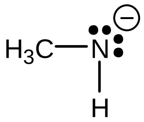
rank =



rank =



rank =



rank =

ChemActivity 9: Core Charge and Inductive Effects

Key New Concepts

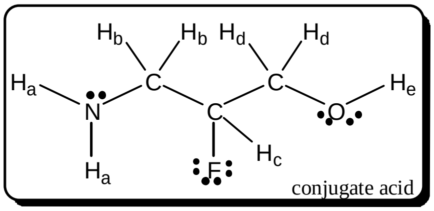
- Core charge as an explanation for what we often call electronegativity
- The “core charge effect” = the electrons of C, N, O and halogens are lower in energy as you move to the right on the periodic table
- “Inductive effect” = long range core charge effect
- Hierarchy of effects: charge effect > core charge effect > inductive effect (note common exceptions involving halides)

Notes to the Instructor

The charge effect, core charge effect, inductive effect, and later, the resonance effect are designed as tools for predicting the relative potential energies of nucleophiles and leaving groups in reactions. An alternative is to memorize a list of pKa’s. Most students find that a combination of these strategies is useful at the beginning: memorize a limited list of pKa’s, but also be able to justify this list based on the above effects.

Quiz 9

1. There are five different kinds of H's on the structure below. They are labeled a-e.
   a) Draw all five different conjugate bases that are possible for this structure in the boxes provided.
   b) Circle the letter in the box of the conjugate base that is lowest in potential energy.

 H_a H_b H_c H_d H_e N C O F conjugate acid	a	b
c	d	e

2. Which type of H is most acidic? [circle one]: **H_a** **H_b** **H_c** **H_d** **H_e**
3. Estimate the pKa you would find in a table for the acid in Q1. [circle one of the following]
   pKa closest to: **0** **2** **5** **14** **33** **45**

Bonus: Write the name of the conjugate acid in Q1.

ChemActivity 10: Resonance Effect

Key New Concepts

- $E \alpha \nu$ and $1/\lambda$
- Wave argument for why an electron in large pi system is low in energy
- Resonance effect

Notes to the Instructor

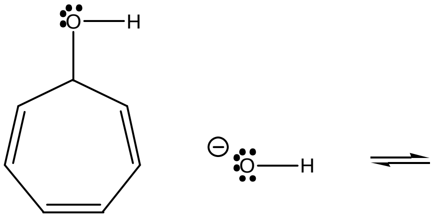
Do not be too discouraged if half your students try to draw resonance structures for compound I in CTQ 4. They have not had much practice with curved arrows or with seeing resonance structures. It may be helpful to refer them back to ChemActivity 3B where the rules for drawing curved arrows were introduced.

Because I work so hard to emphasize the core charge effect, students often memorize that a negative charge on carbon is really high in energy. This makes them think that contributing resonance structures with a negatively charged carbon (such as for enolate ion) actually drive up the energy of the system as compared to an non-resonance stabilized oxygen anion. I have tried to deal with this common misconception using the postal worker analogy in the first homework problem, but it may require further explanation.

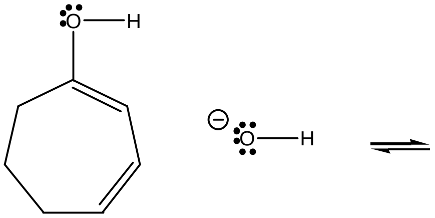
Quiz 10

1. Use curved arrows to show the most likely acid-base reaction for each pair of reactants below.
2. Draw the resulting products including any important resonance structures. (It may help to draw in the missing H's on the reactants. Careful here!)
3. Only one of these two reactions is significantly down hill. Which one? **Rxn I** or **Rxn II** [circle one].

Rxn I



Rxn II



BONUS: One of the following is a correct name for one of the reactants above [circle the one correct name].

2,4,6-cycloheptadiene-1-ol; 1,3-cycloheptadiene-1-ol; 1,3,5-cycloheptatriene-1-ol

ChemActivity 11: Electron Orbitals

Key New Concepts

- Shape energy and electron occupation of s and p orbitals
- Shell #1 comprised of s, p_x, p_y, and p_z
- Orbital overlap giving rise to a sigma bond
- Derivation of each of the hybrid orbital sets (109.5/sp^3, 120/sp^2, and 180/sp)
- p orbital overlap giving rise to a pi bond

Notes to the Instructor

A model set that includes some representation of orbital lobes is needed for this activity. I have ordered orbital lobe pieces that fit with the Prentice Hall models from a Canadian company on the web: www.indigo.com/models. Click on the link to "components."

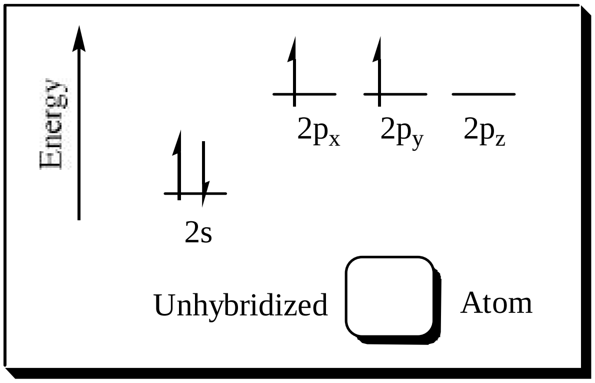
Many books choose to introduce orbitals in the beginning of an organic course, and some even include a rigorous molecular orbital theory treatment. This can be a turn-off at the front of an already intimidating course. I have chosen to introduce orbitals only after students are familiar with the geometry of simple molecules, and to postpone the complexities of MO theory to the second semester. (MO theory is introduced in ChemActivities 24 and 25, where it is needed to explain UV-visible spectroscopy, aromaticity and anti-aromaticity.)

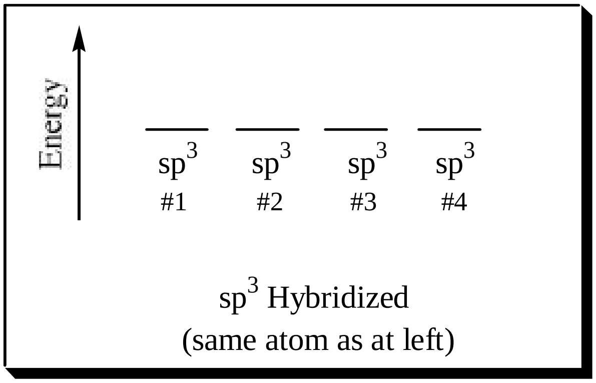
Central to this activity are a series of demonstrations using play dough. Hybrid orbitals are an abstract construction, though a simple one compared to full-blown MO theory. The balls of colored clay make the abstractions more accessible and reveal the simple logic of mixing one s orbital with three p orbitals, and then cutting the mass into four radially symmetrical pieces. This demonstration also explains the eight electron occupation of shell #1, and demystifies the names of the hybrid orbitals sets. Though I have tried to further demystify by first calling them the 109.5, 120 and 180 degree hybrid orbital sets, respectively. It is probably only necessary to do one of the two demonstrations described (and the third one is left as a homework thought-experiment). Note that for simplicity I have ignored the small lobe opposite the main lobe of a hybrid orbital.

The test of this activity is weather students understand why allene is NOT planer. My drawings of the orbitals are clearly not enough to convey all the necessary information. Good models are very helpful. Colored chalk drawings of orbitals and simple molecules are an excellent supplement, particularly if these drawings are generated by students and subjected to peer critique. This can be very time consuming and is best left for a review or laboratory session.

Quiz 11A

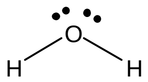
1. Indicate the identity of the atom represented by the unhybridized electron configuration energy diagram below ***left*** by writing the letter of the atom in the box below the energy diagram.
2. Fill in the orbital energy diagram below ***right*** so as to indicate the same atom as on the left, but in a sp^3 hybridized electron configuration.
3. How many half-filled orbitals does this atom have to make bonds with in a sp^3 hybridized electron configuration? ________
4. What percentage of an sp^3 hybrid orbital was originally an s orbital before mixing? _______ **%**

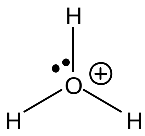


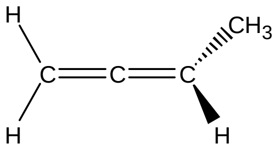


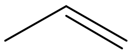
Quiz 11B

1. For each of the following statements, mark the statement as true or false. **If it is false, change the underlined word or words in the statement so as to make it true.**
    a) A π bond consists of four overlapping p orbitals.
    b) A triple bond consists of two σ bonds and one π bond.
    c) An sp^3 hybrid orbital is one-third s orbital and two-thirds p orbital.
    d) An electron in an sp^3 hybrid orbital is lower in potential energy than an electron in a sp^2 hybrid orbital.
2. Mark each non-hydrogen atom below with its hybridization state (sp, sp^2 or sp^3).









Bonus: A molecule with two double bonds is called a "di-ene." For example the structure above is called 1,2-butadiene. Draw 1,5-hexadiene.

ChemActivity 12: One-Step Substitution Reactions

Key New Concepts

- Mechanism of S_N2 reactions
- Nucleophile, electrophile, leaving group
- Transition state
- Chiral inversion
- Effect of activation energy on rate of reaction
- Effect of leaving group, nucleophile, and steric hindrance on E_{act}
- Methyl, primary, secondary, tertiary, and quaternary carbons

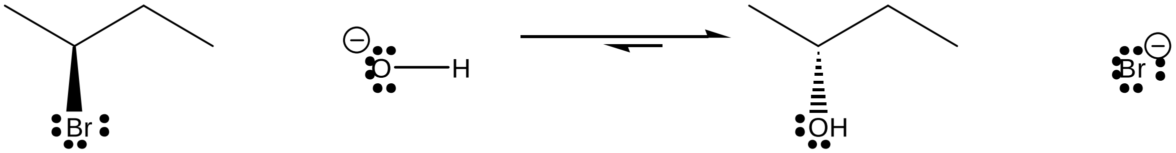
Notes to the Instructor

One thing to watch for is that the name S_N2 is not introduced until ChemActivity 13. For now, I call these reactions "one-step nucleophilic substitution reactions" to emphasize their concerted nature. Another departure from traditional texts is my use of pKa's to estimate C—(leaving group) bond strengths and nucleophile potential energies. This is an extension of the treatment of pKa's in ChemActivity 8, and it gives accurate predictions for many nucleophiles and most leaving groups. Exceptions to watch out for are cyanide and the halides—which are much better nucleophiles than predicted based on the pKa's of their conjugate acids. (Steric factors are discussed in Part B, so I don't consider bulky strong bases an exception.) The sense of the halides, iodide being the best nucleophile, is also not expected based on this simple model. These breakdowns are an opportunity to mention that our models are very simple and useful only for making general predictions, and that there are other models that have been developed to explain such things as iodide being an excellent nucleophile *and* an excellent leaving group. It is useful to point out that the data regarding pKa vs. nucleophilicity is quite muddled. Even considering sterics, it is sometimes difficult to predict nucleophile strength without higher order models such as hard-soft base theory and consideration of solvent effects. For simplicity, I have tried to avoid the exceptions for now and concentrated on nucleophiles that fit predictions made based on pKa's and sterics.

Quiz 12A

For the following pair of reactants:

- a) Use curved arrows to show the most likely nucleophilic substitution reaction.
- b) Use wedge and/or dash bonds to draw the product/s of this reaction.
- c) Predict whether the reaction is **down-hill (exothermic), up-hill (endothermic),** or **neither(thermoneutral)** [circle one].



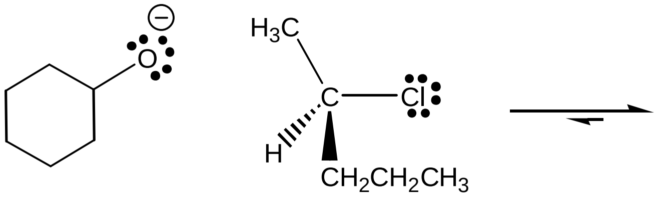
Bonus: Name the carbon containing starting material and product. **Be sure to specify R or S for each**.

Quiz 12B

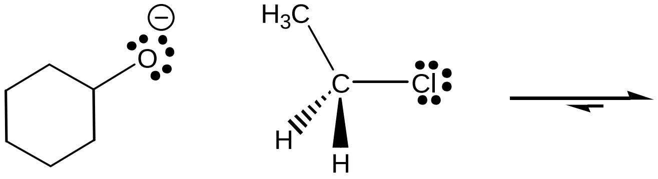
For each of the following pairs of reactants:

- a) Use curved arrows to show the most likely nucleophilic substitution reaction.
- b) Draw the product/s of each reaction (show stereochemistry if appropriate).
- c) Predict which reaction will be faster: **Rxn A** or **Rxn B** [circle one].

A.



B.



Bonus: Write the name of the chiral starting material. Include R or S in its name.

ChemActivity 13: Carbocations and Two-Step Substitution Reactions

Key New Concepts

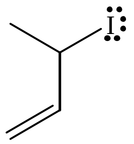
- Polar solvents support ions and carbocations
- Carbocation stability: methyl, primary, secondary and tertiary
- Resonance stabilized carbocations (allyl carbocation)
- Rate limiting step approximation
- Mechanism of S_N1 reactions
- Racimization vs. inversion of stereochemistry in substitution reactions
- Etymology of S_N1 and S_N2 nomenclature
- Effect of sterics and carbocation stability (electronics) on rate and type of substitution
- Possibility of mixed mechanism reactions (e.g. both S_N1 and S_N2)

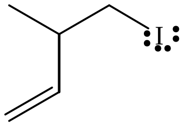
Notes to the Instructor

There is a lot going on in this activity. While each concept is fairly simple, taken alone, it is easy for students to miss the big picture. The final question in Part B is designed to bring it all together. When they do see the big picture, it can be overwhelming since they realize that many reactions have multiple competing mechanisms taking place at the same time. This feeling will only get more intense when elimination is thrown into the mix. I find it useful to allay their fears by promising that we will mostly stick to the clear-cut cases, at least at first.

Quiz 13A

1. Cross out the alkyl iodide below that **cannot** form a carbocation.





2. For the other alkyl iodide, use curved arrows to show how a carbocation could form.

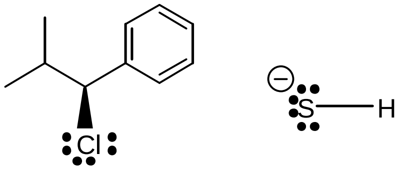
3. Draw the resulting carbocation including all important resonance structures.

4. Choose the statement that best describes the carbocation you drew above.
   A. It is an allyl carbocation with two equivalent resonance forms.
   B. It is an allyl carbocation with some 1^o and some 2^o carbocation character.
   C. It is an allyl carbocation with some 1^o and some 3^o carbocation character.

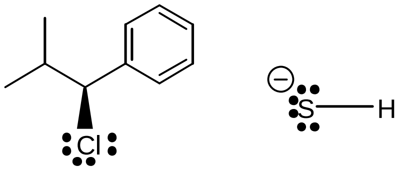
Bonus: Write the correct name of each of the alkyl iodides in Question 1.

Quiz 13B

1. Assume the following pair of reactants undergoes a S_N2 (one-step) substitution reaction. Show the mechanism (curved arrows) and draw the products, including stereochemistry where appropriate.



2. Assume, instead that this pair of reactants undergoes a S_N1 (two-step) substitution reaction. Show the mechanism (curved arrows) and draw the intermediate and final products.



3. Which of the following words best describes the carbocation that you drew in your S_N1 mechanism?

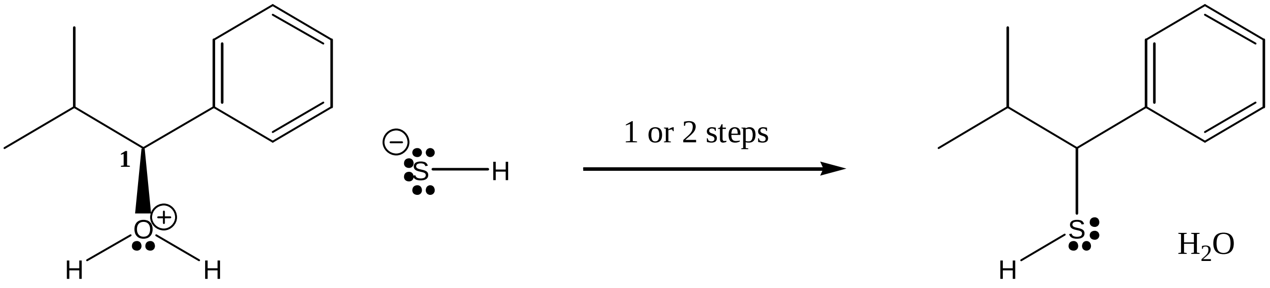
A) primary **B) secondary** **C) tertiary** **D) allyl**
E) benzyl

4. With this pair of reactants, which mechanism is more likely? **S_N2** or **S_N1** [circle one]?

BONUS: Assign R or S to the chiral center in the starting material.

Quiz 13B (alternate)

1. Based on the way it is drawn, is the product **pure R,** or **pure S,** or **a racemic mixture** [circle one]?
2. Is this reaction an **S_N1 reaction** or a **S_N2 reaction** [circle one]?
3. Use curved arrows to show the most likely mechanism of this nucleophilic substitution reaction. **Be sure to draw any intermediate product/s if it is a two-step mechanism.**



BONUS: Choose the best phrase to describe the C labeled with a "**1**" in the starting material: choose from
A) primary carbon, B) secondary carbon, C) tertiary carbon, D) allyl carbon, E) benzyl carbon.

ChemActivity 14: Elimination Reactions

Key New Concepts

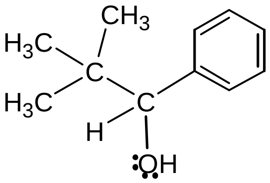
- Hyperconjugation
- E1 and E2 mechanisms (and etymology)
- Strong base vs. weak base as a predictor of E2 vs. E1

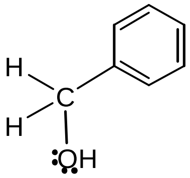
Notes to the Instructor

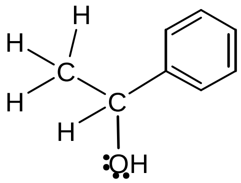
As some texts have done, I use hyperconjugation and the acidity of beta hydrogens as an entry point for E1 reactions. This strategy emphasizes the key skill of identifying beta hydrogens. This ChemActivity contains one of my all-time favorite CTQs. For CTQ 3, most students will initially draw a structure with positive and negative formal charges adjacent to one another. Let this go at first. Most groups will figure out in CTQ 3b, that it is possible to draw a "more important" resonance picture of this zwitterion, namely an alkene! Note that the complexities of elimination, such as product distributions (alkene potential energies) and the interesting stereochemistry of E2 reactions, are addressed in the next activity.

Quiz 14A

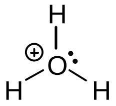
1. Circle the **one** alcohol below that can undergo elimination upon treatment with sulfuric acid and water.







2. The species you circled, upon treatment with H_3O^+, undergoes elimination in three steps. Show the mechanism (curved arrows) of this reaction including all intermediate and final products.

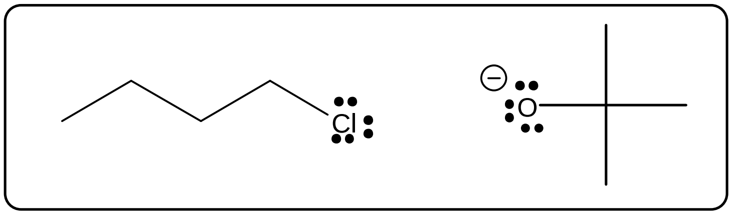


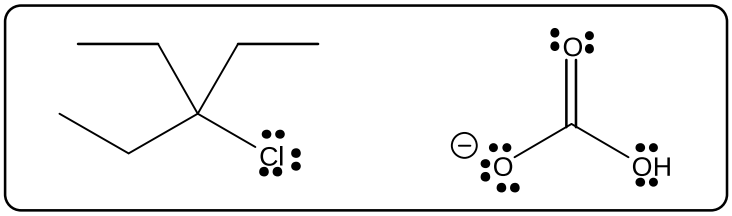
BONUS: The 3rd alcohol in Q1 is named **1-phenyl-1-ethanol**. What is the name of the first alcohol in Q1?

Quiz 14B

One pair below undergoes E1 (two-step elimination). The other pair undergoes E2 (one-step elimination).

- Use curved arrows to show the correct mechanism for each pair.
- Be sure to draw all intermediate and final products as part of your mechanisms.
- **For each, draw in the H that is being eliminated**.





BONUS: Name each of the alkyl chlorides shown above.

ChemActivity 15: Stereochemistry of E2 Reactions

Key New Concepts

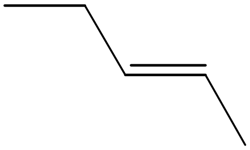
- Catalytic hydrogenation, heat of hydrogenation
- Alkene potential energies
- E vs. Z nomenclature
- Anti-elimination in E2 reactions
- Calculating degree of unsaturation

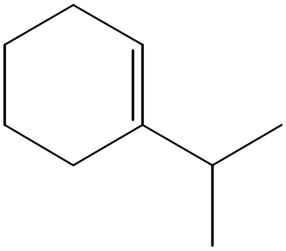
Notes to the Instructor

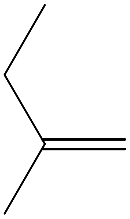
Part B of this activity is very challenging for most students. It is a test of their understanding of many concepts covered so far. It requires them to examine data, think in three dimensions, and visualize the movement of atoms in an E2 mechanism. Traditional models help, but it is very useful to have a model of each transition state. I usually end up bending and mutilating a traditional model to give a sense of how two tertiary centers collapse to give a planer alkene. This activity is a great opportunity to use a computer simulation.

Quiz 15A

1. Assign **E, Z or neither** to each of the following.





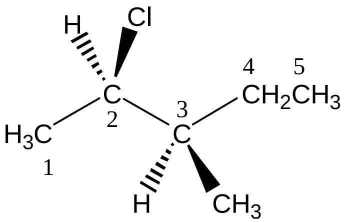


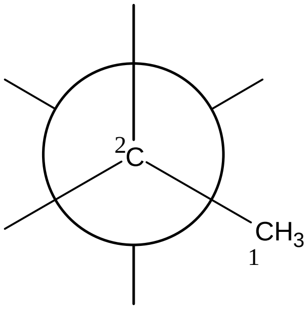
2. Below each structure in Question 1, draw a **constitutional isomer** (not a stereoisomer!) that you expect to be lower in potential energy.

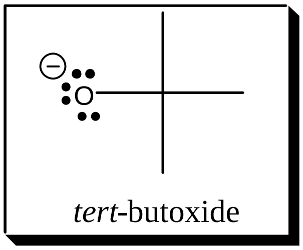
BONUS: Name the first structure listed in Question 1 and name the constitutional isomer you drew below it.

Quiz 15B

1. Complete the Newman projection **sighting down the C_2-C_3 bond** showing a conformation of this alkyl chloride that allows E2 elimination along the C_2-C_3 bond. (When mixed with *tert*-butoxide).

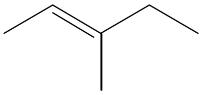


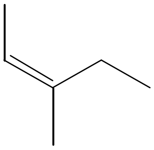


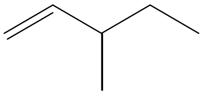


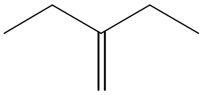
tert-butoxide

2. Circle the **two** alkene products below that are likely to form when the reactants above are mixed.









3. Label one of the circled products "**major product**" and the other one "**minor product**."

BONUS: Name the alkyl chloride in Question 1 including designation of R and/or S, as appropriate.

ChemActivity 16: Spectroscopy

Key New Concepts

- Resonant frequency
- IR spectroscopy
- NMR (proton and ^{13}C)

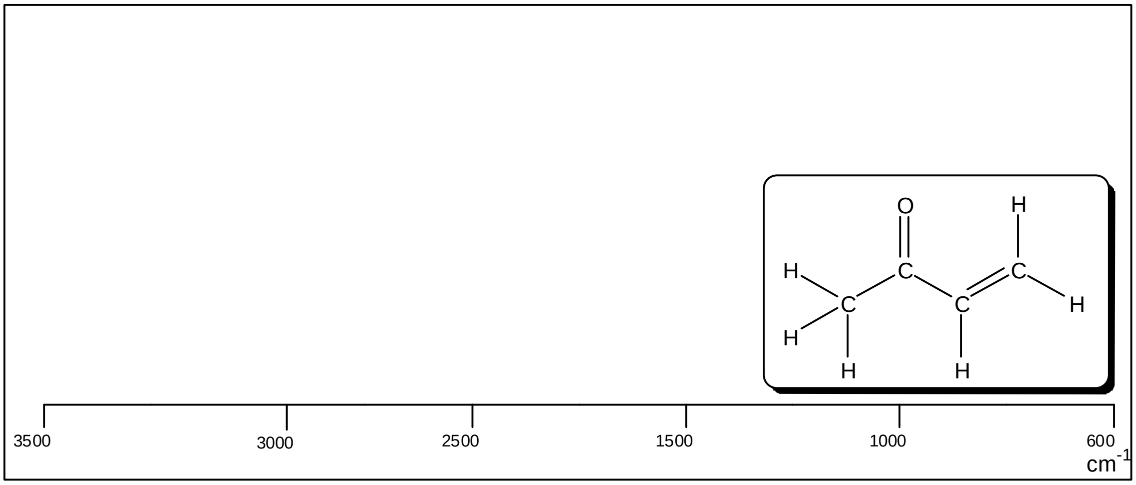
Notes to the Instructor

No attempt is made to explain how NMR works other than an analogy to IR spectroscopy, which is briefly explained in Part A. Most of Parts B and C are devoted to interpretation of NMR spectra. Carbon NMR is introduced before proton NMR in order to put off the issues of integration and H-H splitting. A summary of rules for interpretation of NMR is provided at the very end of the activity.

The concepts of multiplicity, integration and chemical shift are new and totally foreign to students. The integration line seems to be particularly hard for students who have not been exposed to the concept of integration in calculus. CTQ 23 in Model 5 attempts to demystify the integration line. The analogy in CTQ 23d may be offensively anthropomorphic, but it gets across the simple idea that more H's give rise to a larger peak area. The complexities of interpreting the NMR spectra of an impure sample are combined with the concept of using NMR as a quantitative tool in the final CTQ (29). In this capstone question I have chosen the numbers so that the math works out in whole numbers, but many students will still need lots of help. If they are really frustrated you could abandon the quantitative component and focus on NMR as a qualitative measure of purity. In this case, it may make sense to have on hand NMR spectra taken of samples with varying purities.

Quiz 16A

1. Using the information from the table, sketch an IR spectrum that is consistent with the following structure.
2. Label each major peak on your IR spectrum with a wavenumber value (cm^{-1}).
3. Draw a line from each major peak on your IR spectrum to one or more bonds on the structure.

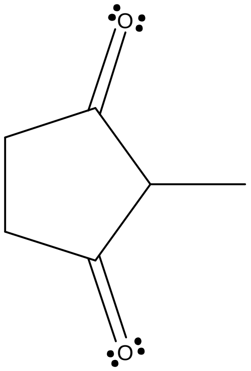


Type of Bond (functional group)	Absorption Range (wavenumbers = cm^{-1})	Type of Bond (functional group)	Absorption Range (wavenumbers = cm^{-1})
$RO-H$ (O-H of alcohol)	3200-3650	C=C bond (of alkyne)	2100-2260
$RC\equiv C-H$ (C-H of alkyne)	3260-3330	C=O (of carbonyl)	1690-1760
$R_2C=\overset{H}{C}-H$ (C-H of alkene)	3050-3150	C=C bond (of alkene)	1620-1680
$R_3C-\overset{H_2}{C}-H$ (C-H of alkane)	2840-3000	C-O bond (of alcohol)	1000-1260

Quiz 16B

1. Label each chemically unique C on the structure below with a letter (a, b, c…etc). If two C's are equivalent label them with the same letter.
2. Next to each C on the structure write **singlet, doublet, triplet** or **quartet** to indicate which type of peak cluster you expect from that C in the coupled ^{13}C NMR spectrum of this molecule.
3. Write a letter in each box below to indicate which C will have a peak cluster farthest left (highest ppm) and which C will have a peak cluster farthest right (lowest ppm) on the ^{13}C NMR spectrum.
4. How many total peaks would you expect on a de-coupled ^{13}C NMR spectrum of this molecule? _____

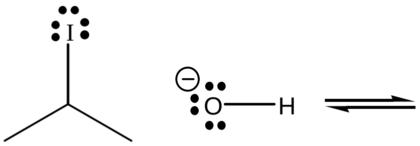
Letter you assigned to the C with a peak cluster at **highest** ppm.



Letter you assigned to the C with a peak cluster at **lowest** ppm.

Quiz 16C

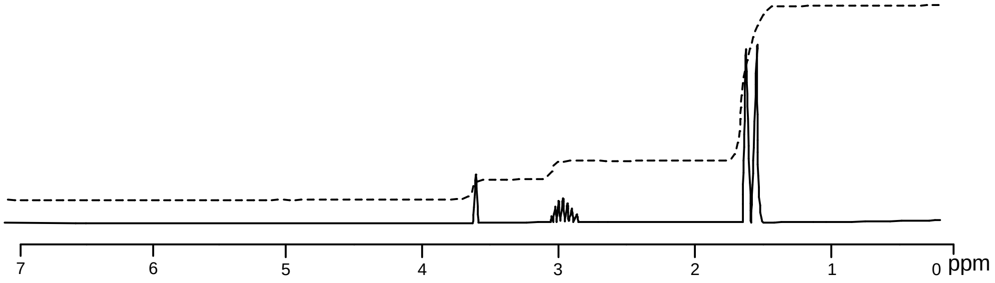
1. The following reactants undergo a mixture of S_N2 and E2 mechanisms producing two different carbon containing products. **Draw** the S_N2 product and the E2 product in the boxes provided.



S_N2 Product

E2 Product

2. You separate the S_N2 product and the E2 product, but you can't tell which is which. To resolve the issue you take a ^1H NMR spectrum of one (shown below). Redraw the appropriate product (S_N2 or E2) on the NMR spectrum and use letters (a, b, c,…etc.) to assign each peak cluster to the H's on this structure.



ChemActivity 17: Electrophilic Addition

Key New Concepts

- Simultaneous collision of three reactants is very unlikely
- Mechanism of electrophilic addition
- Hammond postulate
- Carbocation rearrangement: hydride shift, methyl migration
- Markovnikov's Rule
- Non-reactivity of benzene (foreshadows aromaticity)
- Effect of a catalyst
- Acid-catalyzed electrophilic addition
- Avoidance of high energy intermediates
- Electrophilic addition to a diene (kinetic vs. thermodynamic products)

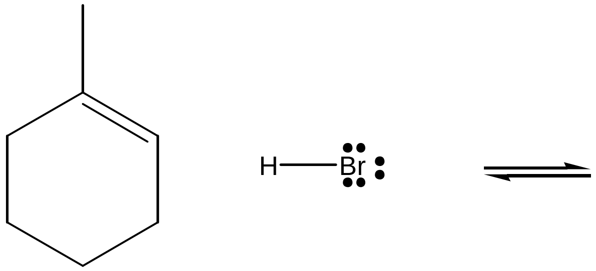
Notes to the Instructor

This activity is the gateway between the part of the course devoted to general principles of energy and bonding, and the part devoted to reactions and mechanisms. It attempts to move students into the realm of being able to propose a reasonable mechanism for a reaction they have never seen before. I have found it very useful to give them some rules of thumb to guide them in this process. The first is that it is unreasonable to propose that three separate species interact with one another in a single step. The second is that an intermediate with a negative charge on C, N, or O should be avoided if another mechanism can be found. I am always surprised at how often I have to repeat both of these. You might consider posting these two rules on the wall so you can just point to one or the other each time you find an offending student mechanism.

The basic electrophilic addition mechanism, Markovnikov's rule, and even carbocation rearrangements do not pose major problems for most students. However, there are three advanced concepts thrown into this ChemActivity: the Hammond postulate, catalysis and kinetic vs. thermodynamic control of a product distribution. You may decide to gloss over at least one of these topics. Many users of the material choose to skip Part D on kinetic vs. thermodynamic control since it is an advanced topic that stands alone. The Hammond postulate is thrown in to justify the use of intermediate energies as an estimate of transition state energies, but most students will not appreciate its importance at this stage. If you only have time to help them with one of these three topics, catalysis would be a good choice since it comes up in future activities and will play a big role in their biology courses.

Quiz 17A

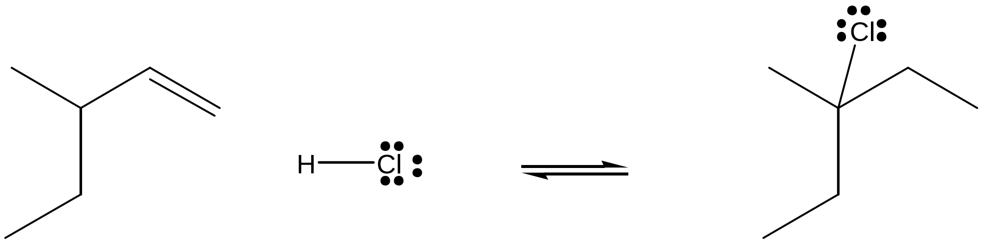
Use curved arrows to show the mechanism of the electrophilic addition reaction that takes place between the two reactants below. Be sure to draw all intermediate and final products as part of your mechanism.



Bonus: Name the hydrocarbon above.

Quiz 17B

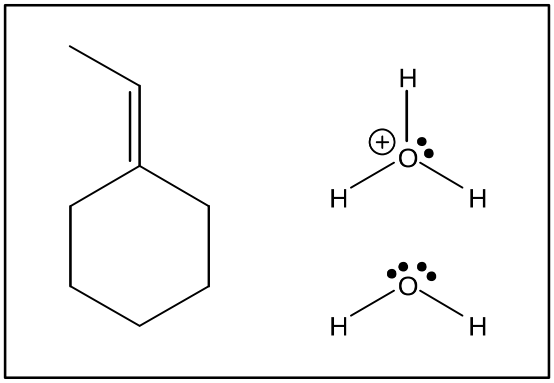
Propose a mechanism to account for the following product. Hint: a carbocation rearrangement occurs as one step in the mechanism. Be sure to draw all intermediate and final products as part of your mechanism.



Bonus: Name the hydrocarbon above.

Quiz 17C

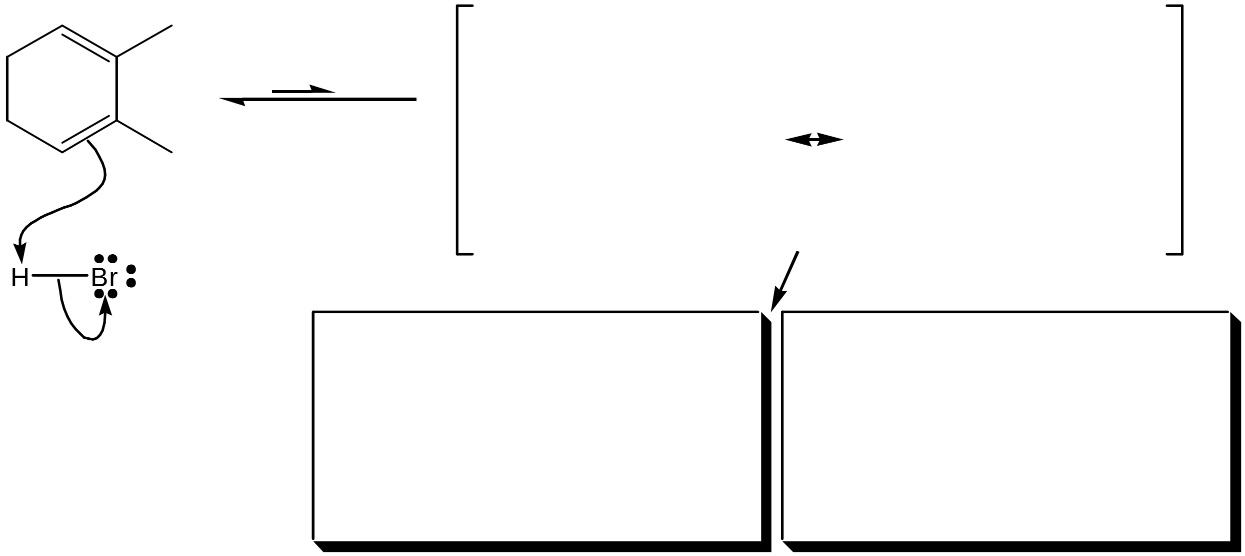
1. Use curved arrows to show the mechanism by which an alcohol forms from the reactants in the box.
2. Circle the catalyst in this reaction **at the point in your mechanism when it is used and at the point when it is regenerated**.



Bonus: Name the alcohol product you drew above.

Quiz 17D

1. The curved arrows below describe the formation of a single carbocation with two resonance structures. **Draw both resonance structures of this carbocation intermediate**.
2. At 30°C (neither hot nor cold) this carbocation reacts with Br^- in two different ways to form a mixture of two alkyl bromide constitutional isomers. **Draw these two alkyl bromide products** in the boxes below.
3. Circle the alkyl bromide product that you expect will be **dominant at high temperature** when all energy barriers can be easily surmounted (this product is called the thermodynamically favored product).



Bonus: Name either alkyl bromide product.

ChemActivity 18: Epoxide & Bromonium Ring Opening

Key New Concepts

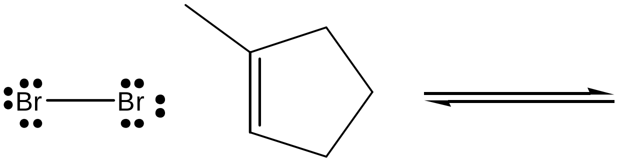
- Ring opening
- Review of the “back-side” nature of S_N2 reactions
- Review of Markovnikov’s Rule
- Review of stereochemistry (particularly diastereomers)
- Regiochemistry vs. stereochemistry

Notes to the Instructor

The stereochemistry of the di-bromination reaction always seems to slip students’ minds on quizzes and exams. This is somewhat understandable given that line-bond drawings of epoxide and bromonium ring opening do not convey the extent of the steric interactions, and that our discussion of S_N2 reactions did not include a MO argument validating back-side reaction. The upshot is that many students are left unconvinced of the *trans* only result. This activity is designed to reinforce that concerted substitution reactions occur via a “back-side” approach mechanism, and to help students work through their general discomfort with stereochemistry and three-dimensional thinking. Note that Exercise 1 is the true capstone of this activity. It is in the homework section so students have access to the answer. If students are struggling, it might be worth discussing this question in class.

Quiz 18

1. The following reactants yield two different major products with the same molecular formula ($C_6H_9Br_2$). Draw both products.



2. Based on the assumption that this reaction obeys Markovnikov's Rule, **circle the Br atom in each product that acted as a nucleophile** during the reaction.

Bonus: The two products you drew are **diastereomers** or **enantiomers** or **constitutional isomers** [circle one] of one another.

ChemActivity 19: Carbon-Carbon Bond Formation

Key New Concepts

- Synthesis
- Functional group transformation
- Carbon-carbon bond formation
- Lithium and Grignard reactions
- Lithium and Grignard reagents can not be used in conjunction with acidic H’s
- Acidity of alkynes
- Memorize reagents for reducing alkynes
- Memorize the names of the functional groups

Notes to the Instructor

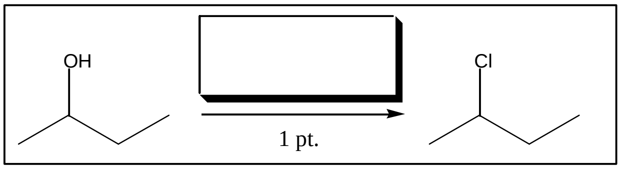
This activity is a mix of several disparate reactions relating to carbon-carbon bonds. Unlike previous activities, an emphasis is placed on learning the reactions rather than on learning their mechanisms. Carbon anions were introduced in CA 8 as hypothetical super-strong bases. Here they learn that lithium and Grignard reagents are by far the most synthetically useful carbon “pseudo-salts.” I allow my students to assume that these reagents act like the hypothetical carbon anions they encountered in earlier chapters.

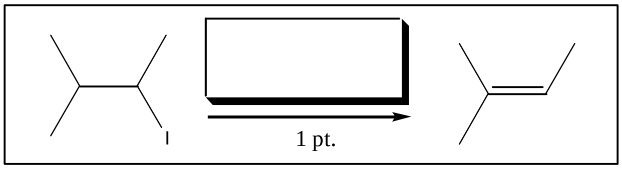
Model 4 is a departure from polar reactions. (Non-polar reactions dominate for the next few weeks if you are using the materials in sequence.) This activity is also an introduction to the functional group approach, which has been avoided up to this point. Now that they have some familiarity with the basic functional groups, it is useful to have them memorize a few of the names. I find this helps them organize what they have learned in preparation for increasingly complex synthesis problems.

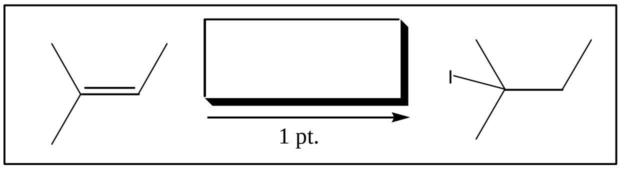
This is a reasonable place to end the first semester, but I try to push through to the end of CA 23, which serves as a capstone and review of electrophilic addition reactions. CA 19 can also be skipped since it does not serve as a conceptual building block for future activities. If you choose to skip CA 19 make sure your students have use of the important synthetic reactions in Models 2,3 and 4. These are listed on the reaction sheets at the end of their workbook.

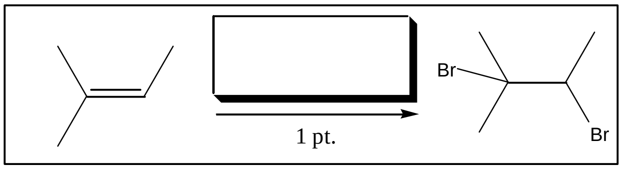
Quiz 19

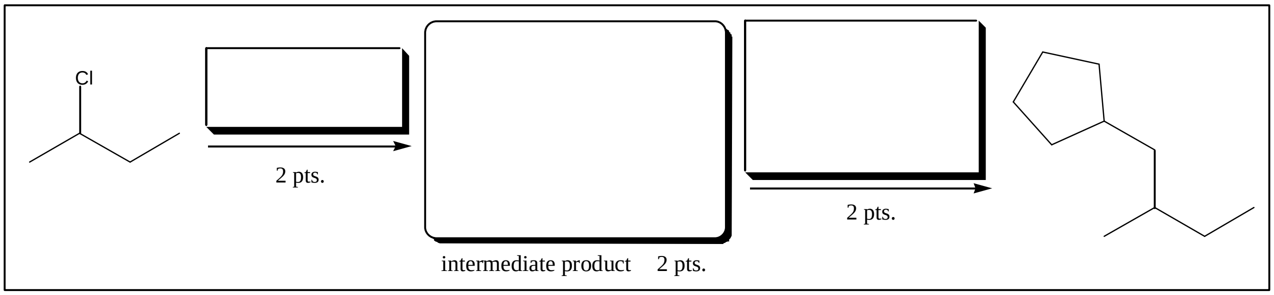
1. Write reagents in the box above each arrow that will accomplish each transformation shown. **Do not** show the mechanisms (curved arrows) of any of these reactions.
2. For the two-step synthesis shown, give possible reagents for each step and the missing intermediate product. (Note: non-carbon containing products are not shown.)











Bonus: Name the product of the elimination reaction above.

ChemActivity 20: Radical Halogenation of Alkanes

Key New Concepts

- Homolytic bond cleavage
- Curved half-arrows (or single-barbed arrows)
- Radical reactions
- H abstraction by a radical
- Relative energies of radicals
- Radicals are unlikely to react with other radicals due to collision statistics
- Radical chain reactions (initiation, propagation, termination)
- Statistics of Photo-halogenation of primary, secondary and tertiary alkanes

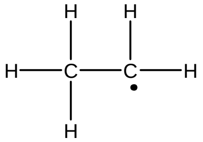
Notes to the Instructor

This activity and CA 21 form a three-day unit on radical reactions. Most of these three days are spent developing the mechanism of radical chain reactions. If you do not wish to cover radical electron pushing, you could skip these two activities (20 and 21) and give a short lecture summing up the synthetic utility of photo-halogenation and radical (anti-Markovnikov) addition of HBr. In any case, I find it is useful to emphasize utility of these reactions. Sometimes I find that devoting so much attention to the mechanisms detracts from the fact that they are among the most useful functional group transformations. In particular, I like to point out that photohalogenation is their only way to functionalize an alkane in a synthesis.

It is important to point out that, in their mechanism in CTQ 7, most students will write down a chain termination step rather than a propagation step. Do not intervene yet. Give them a chance to iron out their own problems when they get to CTQ 9. One key is to get them to accept that a reaction between two radicals is very unlikely due to the low population of radicals relative to other species. The “stadium” analogy in CTQ 8 seems to bring this home for most of them. (This was inspired by real events. While I was living in Philadelphia they built a jail in the sports stadium to process all the fools who got into fights during Eagles games.) The concept is key for their understanding why the methyl radical in the box in CTQ 9 is most likely to react with Br_2. The emphasis on statistics in this Model sets the stage for Model 8, where students are asked to figure out the product ratios for various photohalogenation reactions. A previous version of the matierals included an energy diagram-based explanation for why bromine is more selective than other halogens. While it is an excellent example of how energy diagrams can be used to make product predictions, it served to further distract from the synthetic take-home lessons of this activity.

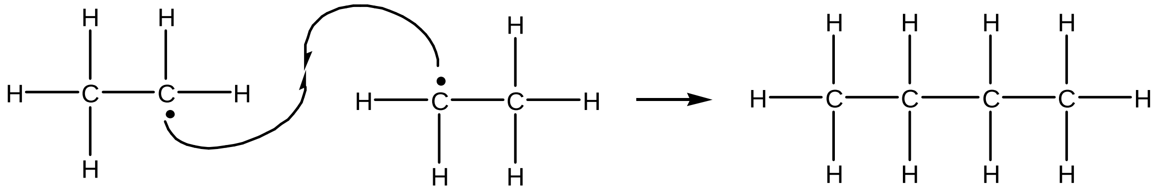
Quiz 20A

When a solution of ethane (CH_3CH_3) and Br_2 is exposed to a strong light source ethyl radical (shown below) is formed as an intermediate radical product.



a) Use curved single-barbed arrows to show how a molecule of ethyl radical can be formed in this reaction. (Hint: start by showing the reaction between Br_2 and light.)

b) A student proposes the following mechanism for formation of butane in this reaction. Explain why formation of butane is very unlikely in this reaction.

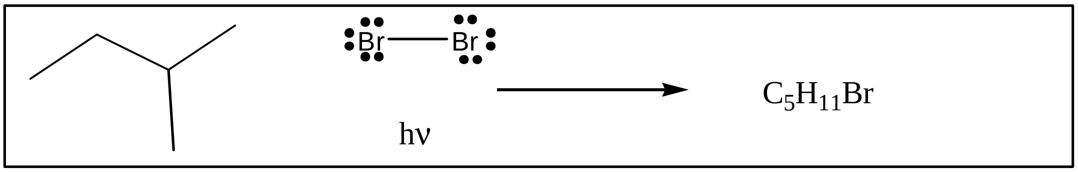


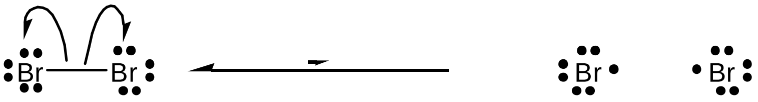
c) Draw the stable organic (carbon-containing) product that is **most likely** to form when ethane (CH_3CH_3) and Br_2 are exposed to a strong light source.

Quiz 20B

For the following radical bromination, use curved arrows to show propagation steps leading to the **most likely product** with molecular formula $C_5H_{11}Br$.

- The initiation step is shown for you.
- **DO NOT show any termination steps** or other statistically unlikely steps.





initiation step

Bonus: Name the product of with molecular formula $C_5H_{11}Br$.

ChemActivity 21: Anti-Markovnikov Addition of H-Br

Key New Concepts

- Reaction of a pi bond with a radical
- Photohalogenation vs. radical addition
- Radical initiation
- Radical addition vs. polar addition of H-Br (Markov. vs. anti-Markov.)
- Synthetic utility of anti-Markovnikov addition

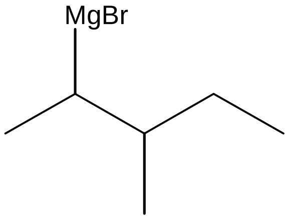
Notes to the Instructor

This activity is a continuation of CA 20, and it is best to do these one after another. By this point, most students are reasonably comfortable with the photohalogenation chain reaction mechanism. However, it can be very confusing when they find in Model 1 of this ChemActivity that radical addition of HBr is also initiated by the formation of bromine radicals. They may ask with exasperation, "How can we tell the difference between the two?" The key difference to emphasize is that in photohalogenation, Br_2 is the most abundant radical quencher in solution, whereas in radical addition, HBr is the most abundant radical quencher. It may be useful to point out what happens if the bromine radical undergoes H atom abstraction instead of reacting with the pi bond in Rxn II of Model 1. (In the presence of large amounts of HBr this leads to regeneration of the starting material.) Some students may ask the legitimate question of why Br_2 is not added across the double bond in Rxn I of Model 1. Time permitting, you could ask such a student to draw the radical that is generated in each case. (Br_2 addition proceeds via an ordinary secondary radical, whereas H-atom abstraction (photohalogenation) in Rxn I of Model 1 proceeds via a lower energy allyl radical, therefore the latter is favored.)

Quiz 21

Construct a reasonable synthesis that yields the following Grignard reagent (as the major product).

- You must start from 3-methylpentane.
- Write the reagents for each step over a reaction arrow and draw the stable, uncharged products that form along the way. **Do not draw charged or radical intermediates. Do not show any mechanisms**.



ChemActivity 22: Hydroboration/Oxidation

Key New Concepts

- Lewis acids and bases
- Reactivity of boron reagents
- Mechanism of hydroboration (de-emphasized as compared to result)
- Stereochemistry and regiochemistry of hydroboration addition
- Reagents for oxidation of C-H sigma bonds
- Reagents for oxidation of carbon carbon pi bonds
- Reagents for oxidation of C=C double bonds

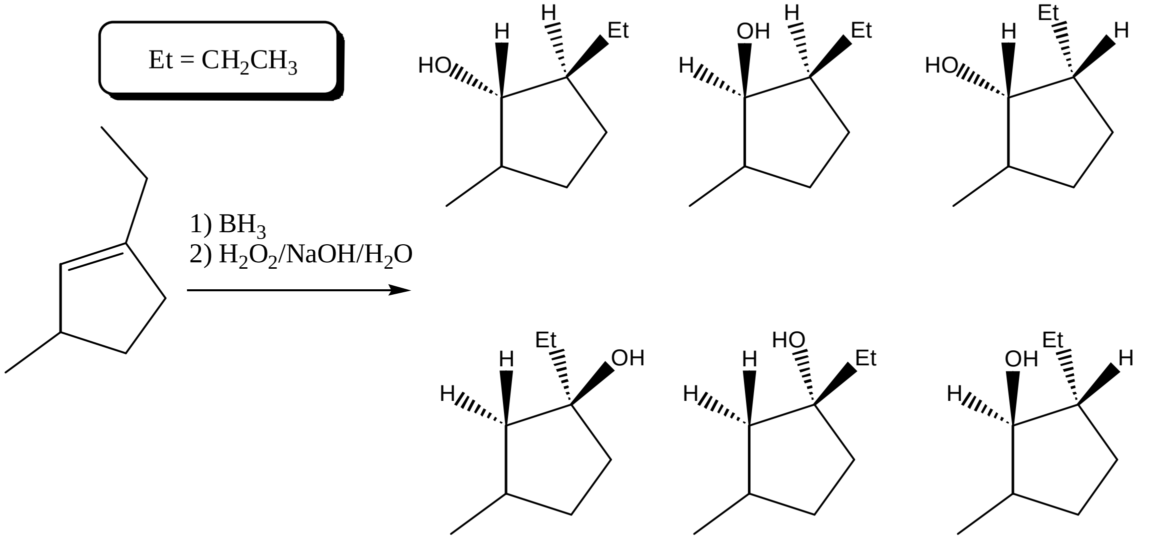
Notes to the Instructor

This activity is the last of a series of four activities which have dealt largely with non-polar reactions. Part A focuses on hydroboration. The mechanism of the reaction is de-emphasized since it is quite unlike any polar or radical mechanisms they have encountered so far. Instead of asking students to devise a mechanism, they are asked to consider if the mechanism proposed in the activity explains the observed stereochemistry and regiochemistry.

Part B, on oxidation reactions, is unrelated to Part A except for the fact that hydroboration-oxidation constitutes a very useful new synthetic tool: anti-Markovnikov addition of water across a double bond. There are no mechanisms discussed in Part B. Instead students are asked to analyze which bonds are susceptible to successively stronger oxidation reagents. The hope is that they will develop a sense of what oxidations are possible and that this will help them memorize the appropriate reagents.

Quiz 22A

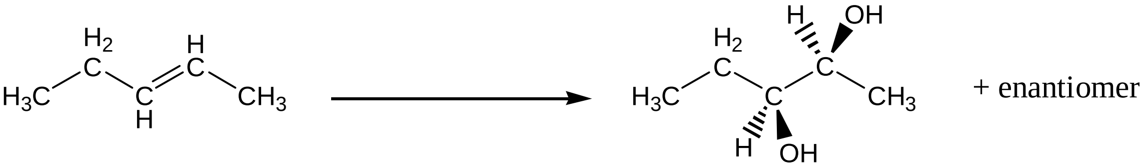
1. Circle each product that is likely to form in the following reaction.
2. Label each circled product as **Markovnikov** or **anti-Markovnikov**.
3. Label each circled product as a **syn addition** or an **anti addition** of the components of water.

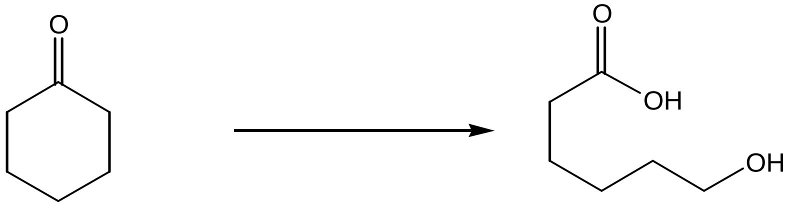


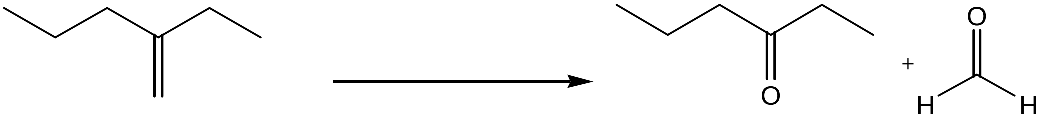
Bonus: Name the starting alkene.

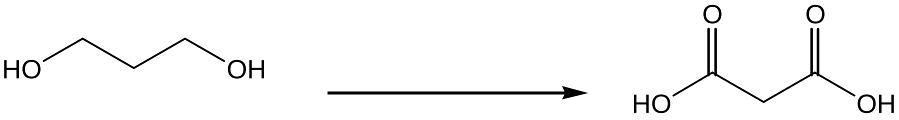
Quiz 22B

Three of the four reactions below are possible using reagents from ChemActivity 22B. One of the reactions below is not possible using these reagents. Cross out the reaction that is not possible and **write appropriate reagents over the reaction arrow for each of the other three**.









ChemActivity 23: Electrophilic Addition to Alkynes

Key New Concepts

- Keto-enol Tautomerization
- Electrophilic addition to an alkyne

Notes to the Instructor

This is the final activity of my first semester sequence. It serves as a review of several key concepts including electrophilic addition, orbitals, Markovnikov’s rule and synthesis. Also, I feel it is appropriate to end the semester talking about polar reactions since they form the bulk of the course. (Despite the fact that the previous several activities focused on non-polar reactions.) Both of the new concepts introduced in this activity (tautomerization and electrophilic addition to alkynes) are modest extensions of concepts from previous activities. If you have fallen behind, this activity is a prime candidate for the chopping block. You may even choose to skip this activity and build final exam questions around either of these concepts. I like to introduce variations on a familiar concept in the exam setting. (Such as asking them to construct a mechanism for a tautomerization or electrophilic addition to an alkyne.) This gives them practice applying learned concepts to unfamiliar situations (this is the structure of many MCAT questions), and tells me who is learning concepts and who is memorizing results. Many of my first semester final exam questions touch on concepts from the *second* semester! By now, students have been exposed to most of the important concepts needed for both semesters of this course. I know I have succeeded with a student if he or she views second semester topics as new applications of old ideas.

Quiz 23

1. Draw an enol that is likely to undergo tautomerization.

2. Use curved arrows to show the mechanisms of this tautomerization and draw the resulting keto product.

Bonus: Write the correct name of your starting enol.

ChemActivity 24: Conjugation

Key New Concepts

- s-cis and s-trans dienes (the gray area between conformers and isomers)
- Conjugated double bonds
- Theories as human-invented, flawed and limited explanations for observation
- Introduction to molecular orbital theory
- MO diagrams: bonding, non-bonding, anti-bonding, nodes, electron occupation
- Making simple predictions using MO diagrams
- Drawing simple MO diagrams
- MO descriptions of excited states
- UV-visible spectroscopy

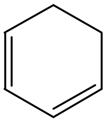
Notes to the Instructor

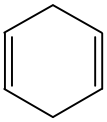
This is my first activity in the second semester. You may think this is a really poor choice since Part B deals with one of the most abstract and mystifying topics in the course: molecular orbital theory. My attitude is that there is no good place to put MO theory in an introductory course. It is too complex to cover well in one class period, yet is does not play an important enough role in the rest of the course to warrant devoting more time. I have found that the concepts of MO theory go right over the heads of most of my students, even if I devote several class periods to the topic. Part B gives an introduction to students who will go on in chemistry, but its primary purpose is to give me an opportunity to point out that the models we have been using (Lewis, hybrid orbitals, etc.) are fallible, over-simplified constructions that serve as antecedents for successively more complex models with narrower but more precise predictive powers.

Part A is reasonably light and presents a picture of orbitals that is consistent with their experiences from first semester. In my courses there is quite a bit of personnel change during the first week. The important concepts from Part A are light enough that students who join late can easily pick them up, and the concepts from Part B do not play a large role in subsequent activities (except for the MO theory explanation for Huckel’s rule in CA 25B).

Quiz 24A

1. One of the following rings is not planar, the other is nearly planar. That is, for one of them, the lowest potential energy conformation has all six carbons very close to a single plane (the plane of the paper). **Circle the nearly planar ring**.

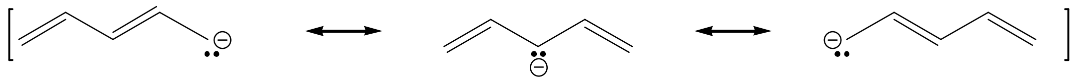




2. In one sentence, explain the energy advantage of being planar (for the nearly-planar ring).

Bonus: Name each diene above.

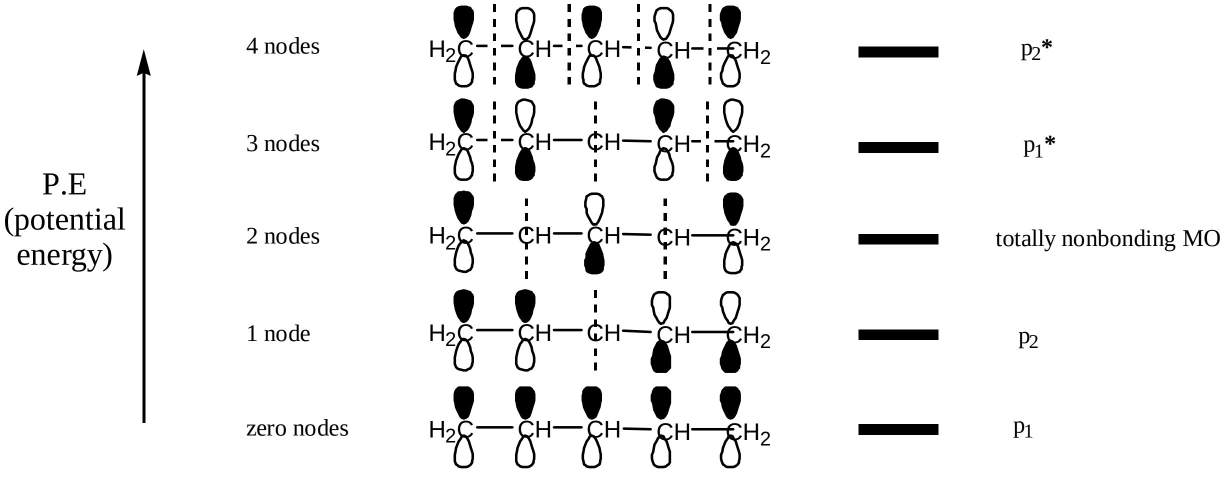
Quiz 24B



The MO diagram for the π system of this anion is shown below without electrons. **Complete the MO diagram below by adding the correct number of** p **electrons**. (Assume the lone pair resides in a p orbital.)

a) Label the Highest Occupied Molecular Orbital (HOMO) and Lowest Unoccupied Molecular Orbital (LUMO).

b) Predict which (if any) of the following C-C bonds **will get longer** (weaker) if one electron is excited from the HOMO to the LUMO. **C_1-C_2** **C_2-C_3** **C_3-C_4** **C_4-C_5** [circle all that apply]



Bonus: Write the name of the two dienes that result if the anion (at top) is treated with dilute acid (H_3O^+).

ChemActivity 25: Aromaticity

Key New Concepts

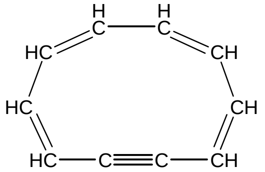
- Stability of benzene
- Racetrack model for aromaticity: (cyclic, planar, continuous, 4n+2 electrons)
- Huckel's Rule
- MO explanation for Huckel's rule
- Anti-aromaticity (cyclic, planar, continuous, 4n electrons)
- The anti-aromatic molecule: cyclobutadiene

Notes to the Instructor

Aromaticity, particularly Huckel's rule, seems like magic without a molecular orbital theory explanation. This explanation, given in Part B, is the justification for introducing MO theory in CA 24B. Some students will enjoy this explanation. For the others, the "magic 4n+2 electron racetrack" will have to do as a model. Given enough examples and counterexamples, most students come away with a working definition of aromaticity as long as they can predict when a molecule can be planar. In terms of definitions, it is useful to emphasize that a molecule is considered aromatic if it contains an aromatic pi system (that is, it can have non-aromatic parts). The other major sticking point, predicting which type of orbital a lone pair will reside in, is addressed in Part B. I encourage students to anthropomorphize this and think from the perspective of the electron, asking themselves: "If I were an electron, would I 'choose' to squeeze into a p orbital?" (The answer is yes if doing so creates an aromatic pi system.) Giving the electron pair a say in the matter sets students up for the electron "choosing" to NOT reside in a p orbital so as to avoid anti-aromaticity.

Quiz 25A

An argument between two students regarding the molecule below is about to get ugly. Can you help them?

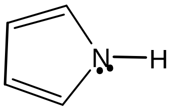


They agree that if the molecule is planar there is an uninterrupted "racetrack" of parallel p orbitals, but they disagree about the number of p orbitals in that racetrack and the number of pi electrons that are racing around it.

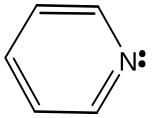
- Student **X** argues the molecule has 10 π electrons in a racetrack consisting of 10 parallel p orbitals.
- Student **Y** argues the molecule has 12 π electrons in a racetrack consisting of 12 parallel p orbitals.
  a) It seems Student **Y** is arguing that the molecule is **aromatic** or **not aromatic** [circle one].
  b) Take sides: Who is right? Student **X** or Student **Y** [circle one]
  c) Briefly explain where the ***incorrect student*** went wrong in his reasoning.

Quiz 25B

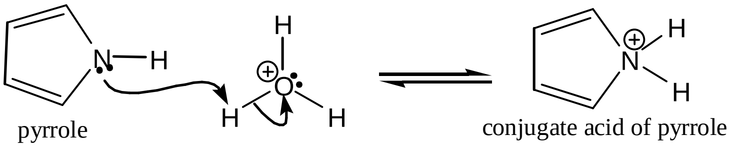
pyrrole



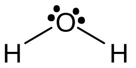
pyridine

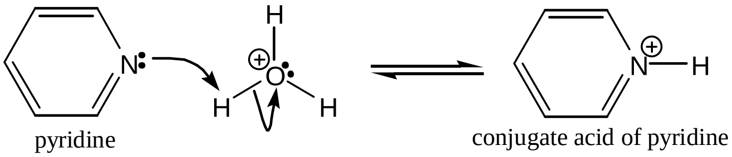


1. Label the lone pair on each nitrogen above with the **type of orbital it resides in**. (According to hybridization theory, not MO theory.)
2. For the two conjugate acids below, one has a pKa = 0, and the other has a pKa = 5. **Label each conjugate acid below with its correct pKa value.** (Hint: it may help to answer the bonus question first.)

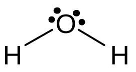


pKa =





pKa =



Bonus: Circle the name (below) of each compound that is aromatic:

pyrrole **pyridine** **conj. acid of pyrrole** **conj. acid of pyridine**

ChemActivity 26: NMR of Aromatic Molecules

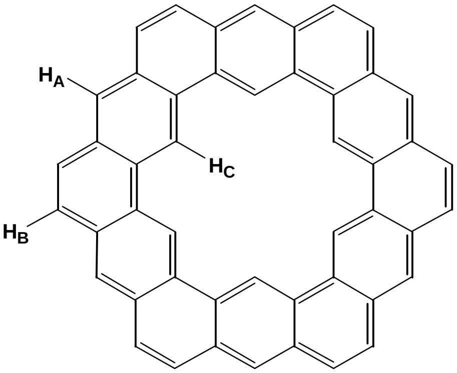
Key New Concepts

- Review of proton NMR
- Nomenclature of substituted benzenes
- Aromatic region in proton NMR
- Ring current effect

Notes to the Instructor

This activity is designed to give students a review of proton NMR, which was introduced in the first semester, but will continue to be important in upcoming activities. The new concepts should not cause problems for students who are comfortable with NMR. I find that students who struggle with this material are mostly having trouble identifying which hydrogens are equivalent. Usually, this inability to quickly identify the symmetry of a molecule stems from an inaccurate or underdeveloped 3D mental picture of the structure.

Quiz 26



	1 # of H's	**2** splitting (s,d,t,q,m)	**3** approx. ppm range
H_A			
H_B			
H_C			

The aromatic molecule above has three different kinds of H's: H_A, H_B, and H_C. One of each type of H is shown. Only one of its many resonance structures is shown.

a) **Fill in Column 1,** above, by writing the number of H's of each type.

b) **Fill in Column 2**, above, by indicating whether this H would show up as a singlet, doublet, triplet, quartet or multiplet on a ^{1}NMR spectrum.

c) **Fill in Column 3**, above, by writing the correct ppm range for each H. Choose from… **<0ppm; 1-4ppm; 6-9ppm;**

ChemActivity 27: Polymerization Reactions

Key New Concepts

- Polar mechanism for styrene polymerization
- Biosynthesis of lanosterol
- Enzyme control of a mini-polymerization

Notes to the Instructor

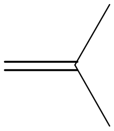
There are many interesting concepts associated with polymer chemistry that are not normally included in an introductory organic course. Perhaps this is an error on our parts given the ubiquity of polymers in everyday life. The title of this activity may lead you to believe that these topics will be covered. Alas, students will have to wait for a polymer course to learn about step-growth polymerizations, glass transition temperatures, copolymers, Ziegler-Natta catalysts, thermoplasticity, etc.

This activity introduces only a simple polar polymerization mechanism. From there it builds to an enzyme-controlled mini-polymerization (biosynthesis of lanosterol). I find these two topics thematically related even though the latter is not a polymerization (and you should point out to your students that steroids are not polymers!). In previous activities students have learned that reactions involving more than two molecules are statistically impossible. With this example, I hope to wow them with the power of enzyme catalysts.

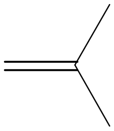
Ultimately, my goal is to set students up for the rudimentary Diels-Alder mechanism presented in the next activity (ChemActivity 28). ChemActivity 27 attempts to give students a taste of several mostly-unrelated topics. I have made an attempt to tie them together (perhaps unsuccessfully). Several times I have taught this course opposite a traditional section, and I was compelled to cover most all topics covered in the other section. If you are not in this situation, you may choose to skip this activity and the next one (Diels-Alder reactions) since the topics covered in these two activities are tangential to the main thread of the course.

Quiz 27

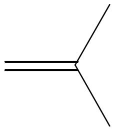
$E^{\oplus}$



Monomer



Monomer



Monomer

1. Draw the carbocation that might exist after the **three monomers** above are linked together in the presence of a Lewis acid catalyst (E^+). This is the beginning of a polymerization reaction. Hint: be sure your product has the right number of carbons. **You do NOT need to show the mechanism of this reaction**.

2. (2pts) Draw a shorthand representation of the polymer that will result if hundreds of these monomers link together.

Bonus (1pt): Write the name of the monomer.

ChemActivity 28: Diels-Alder Reactions

Key New Concepts

- Concerted, aromatic-like transition state for D-A reactions
- Diene and dienophile
- Stereochemistry of D-A reaction
- Frontier orbitals: HOMO and LUMO
- Molecular orbital explanation for stereochemistry of D-A reaction
- Effect of electron withdrawing and donating groups on HOMO and LUMO
- Effect of electron withdrawing and donating groups on rate of D-A reaction
- Conrotatory vs. disrotatory

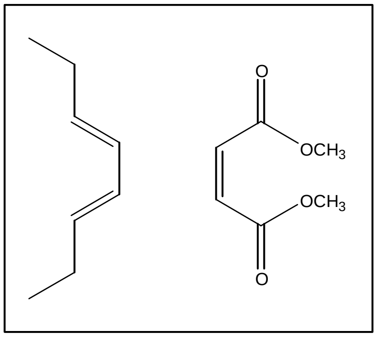
Notes to the Instructor

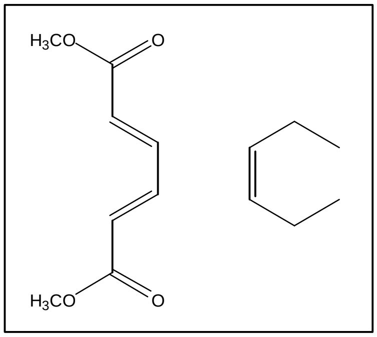
If you are like me, you have a stack of organic texts in the corner of your office. I have found that every author makes an attempt to fit Diels-Alder into the introductory sequence, but none are particularly successful, in my opinion. ChemActivities 27 and 28 are my own attempt. Pericyclic reactions are a stand-alone topic, usually left to an advanced course, but for some reason Diels-Alder is included in the introductory sequence. If you are short on time and are not compelled to cover every traditional topic, CAs 27 and 28 can be skipped without jeopardizing students' understanding of subsequent activities.

The stereo and regio-control of the Diels-Alder reaction make it very synthetically useful, and this activity focuses on these aspects of the reaction, not the mechanism. A polar cartoon mechanism is provided to help students keep track of electrons, while the pericyclic mechanism is touched upon only briefly. The latter is included to justify the unusual stereochemistry of the reaction, and to give you another opportunity to show off the utility of molecular orbital theory. Discussion of the 4n+2 electron "aromatic" transition state in a D-A reaction is my attempt to foreshadow the Woodward-Hoffmann selection rules, but you are much more likely to appreciate this than your students.

Quiz 28

Only one of the following pairs of reactants undergoes a fast Diels-Alder reaction. For this pair, draw the most likely Diels-Alder product. **Be sure to specify stereochemistry where appropriate.**





ChemActivity 29: Electrophilic Aromatic Substitution

Key New Concepts

- Mechanism of EAS
- Characteristics of electrophiles capable of EAS
- *Ortho-para* directing effect of an alkyl group
- Steric effects of an alkyl group
- Activating and deactivating groups for EAS
- "Second order" resonance structures
- Resonance donating groups are *o/p* directors
- Resonance withdrawing groups are *meta* directors
- Directing effects on di-substituted rings

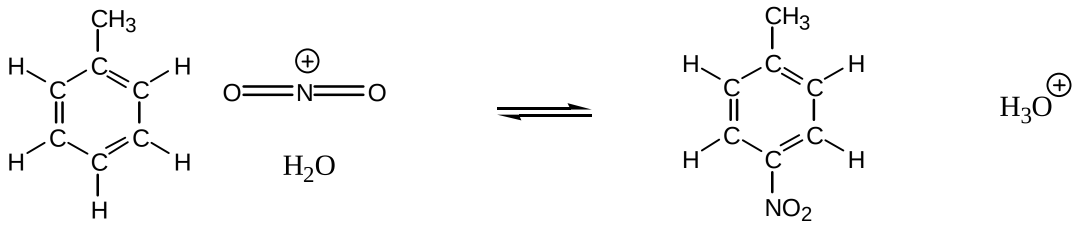
Notes to the Instructor

Texts approach directing effects in EAS with one of two strategies. The one that makes the most sense to me involves drawing all resonance forms of each intermediate and predicting which one is lowest in potential energy. This is developed in Part B. Students can handle this, but when it comes to resonance arguments they much prefer the treatment discussed in Part C, Model 5 involving what I call "second order resonance structures." Up to this point in most organic texts, resonance structures are entities that depict charge distribution in an ion. Suddenly, in the EAS chapter of many texts a variation on resonance structures is used to predict locations where increased positive and negative charge reside on a neutral species. (This treatment is also commonly used to emphasize the polarity of the carbonyl group by showing a resonance contributor with a full positive charge on carbon and a full negative charge on oxygen.) I always found it quite surprising that a species with two non-zero formal charges could be a significant contributor compared to a species with no formal charges. The term "second order resonance structure" helps make a distinction between these two types of predictive drawings.

Lewis acid catalyzed EAS reactions including Friedel-Crafts reactions are an important topic, however time constraints have led me to delegate this subject to an at-home Mini-activity, which can be found at the end of the Exercises for Part D. Time permitting, you may choose to devote a class period to this activity.

Quiz 29A

1. Use curved arrows to **show the mechanism** of the following transformation. It is not a one-step process so be sure to **show all intermediates**. (All species needed for the reaction are shown.)

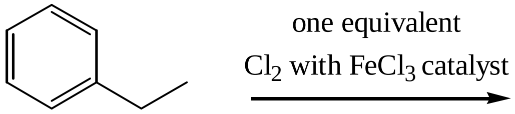


2. NO_2^+ is not a stable species. You can NOT bottle it and store it on the shelf. What two reagents (actual chemicals you can find in a bottle in the lab), when mixed, give NO_2^+ for this reaction?

Bonus: Write the names of both aromatic structures at the top of the page (reactant and product).

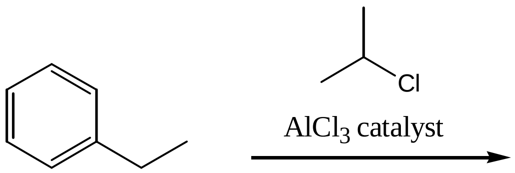
Quiz 29B

1. Two isomeric (aromatic) products are observed in the following reaction. Draw both.



(do NOT show the mechanism/curved arrows)

2. One aromatic product is observed in the following reaction. Draw it.



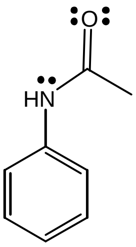
(do NOT show the mechanism/curved arrows)

3. The fact that the first reaction gives two major products and the second reaction gives one major product is best explained using **an electronic argument** or **a steric argument** [circle one].

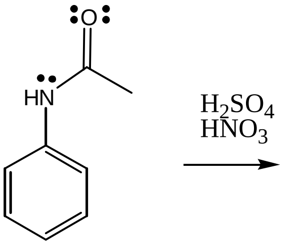
Bonus: Write the names of both aromatic **products** in the first reaction (Question 1).

Quiz 29C

1. In the brackets draw 2nd order resonance structures of the starting material showing electron donation into or electron withdrawal from **the ring**.
2. In the box at the bottom of the page, draw the most likely product or products of the reaction.



Draw Second Order Resonance Structures of the Starting Material

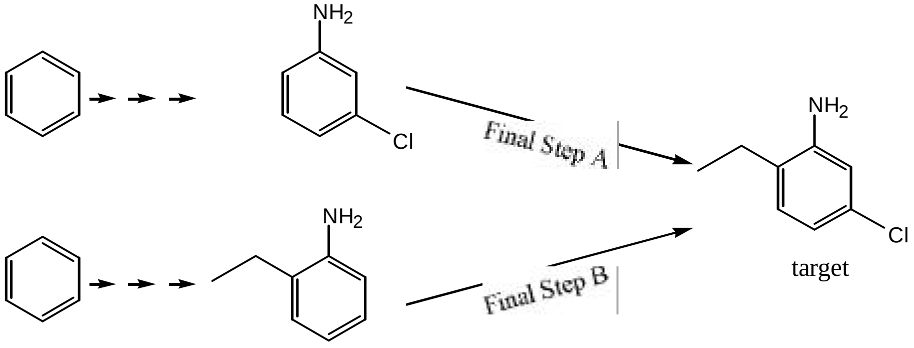


Draw the most likely Product or Products

Bonus: Which do you expect to undergo EAS faster: aniline or the starting material shown above?

Quiz 29D

The target shown can be made from benzene. Consider the final step of two alternate synthetic routes.



Most Likely Product of the worse Final Step

a) Which final step is better: **Final Step A** or **Final Step B** [circle one]?

b) Over each final step reaction arrow, write reagents that best accomplish the substitution shown. (**Note: Reagents for the worse final step give a very low yield of the desired target**.)

c) In the box above, draw the **single** most likely aromatic product that would result from the worse final step (the one you did NOT choose in part a).

Bonus: Name the target.

ChemActivity 30: Synthesis Workshop I

Key New Concepts

- Retrosynthesis
- Redox reactions that change an o/p director into a meta director or vice versa
- Sulfone as a protecting group in EAS
- Difficulty of fully reducing a benzene ring

Notes to the Instructor

This activity was added to provide more in-class discussion of synthesis. You may choose to skip this activity, but if synthesis is a priority of your course you should probably replace it with a discussion of synthesis. By skipping this activity your students will also miss my introduction to several synthetically useful redox reactions. (These are also found in the appendix on reaction sheet R6.)

ChemActivity 19 introduced the idea that each step in a synthesis accomplishes either a functional group transformation or a modification of the carbon backbone. Here retrosynthesis is added as a conceptual tool for working out synthesis problems. In addition, several new redox reactions are introduced to widen the scope of possible synthesis problems. As I am sure you have found, creating and testing good synthesis problems is a task wrought with many pitfalls. There are several problems in the Exercises portion of this activity, but I am sure that students would benefit from doing additional problems of your creation. The last homework problem suggests that any student with a clever, short synthesis should submit it to the instructor for possible use in the upcoming quiz. I have never been able to use a student generated synthesis, verbatim, so this is not a big time saver, but students say making up there own problem helps them understand synthesis.

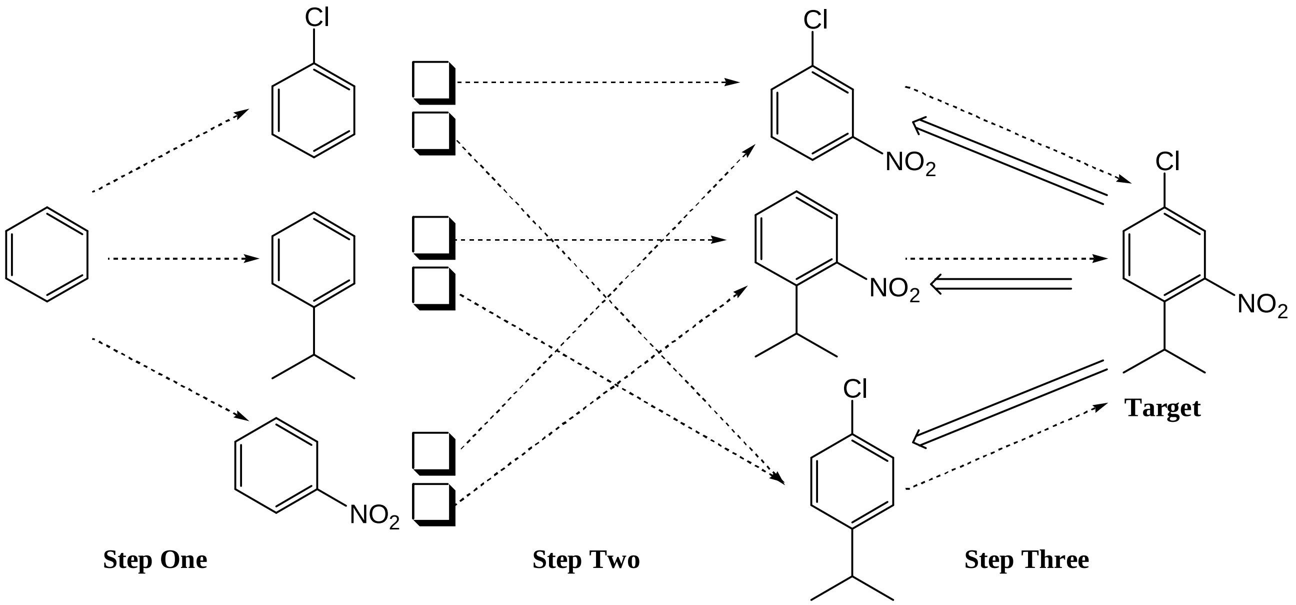
Quiz 30

Shown below are many pathways (some good, some bad) for making the target from benzene in three steps.

1. Retro arrows in **Step 3** show you three ways to pull apart the target. One of the forward reactions in **Step 3** will give a very low yield of target. **Put an X** on the reaction arrow for the **"worst choice" for Step 3.**

2. Consider the six possible **Step 2**'s. **Put an X** in the box for **each reaction that will not work well** because of the wrong directing effects or unfavorable electronic or steric effects.

3. **Darken** a set of dotted reaction arrows showing the **best** pathway from benzene to the Target.



ChemActivity 31: Nucleophilic Addition to a Carbonyl

Key New Concepts

- Addition of a Grignard (or similar reagent) to an aldehyde
- Addition of water (or other weak nucleophile) to an aldehyde: hydrate or hemi-acetal formation
- Using LeChatelier's principle to maximize yield
- Irreversible addition-elimination reactions (with an acid chloride)
- Reversible addition-elimination reactions (acetal and imine formation)

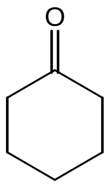
Notes to the Instructor

LeChatelier's principle plays a central role in this activity, but I have found most students do not have a working knowledge of this most central of equilibrium concepts. I have struggled to come up with a macroscopic example of an equilibrium involving two reactants that can be shifted by adding more of either reactant, or by taking away product. The "Singles Dance" analogy is the best I could come up with. If you have a better analogy, I would love to include it in the next edition.

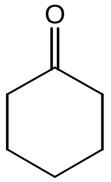
You will notice that acid chlorides make a brief appearance in this activity (they are covered further in CA 41). I use acid chlorides as a simple example to introduce addition-elimination, rather than throwing students headlong into the proton shuffling associated with acetal and imine formation. A secondary hope is that introducing these reactions together will reinforce the fact that acid chloride addition-elimination reactions also proceed via a tetrahedral intermediate. Despite my efforts, some students continue to show acid chlorides reacting in one concerted step (nucleophile replaces chloride). Part B of this activity looks short, but you have to push them through the first page to give them sufficient time to wrestle with the last mechanism question on imine formation.

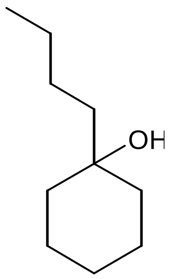
Quiz 31A

1. Draw a 2nd **order resonance structure** of the molecule below that shows the polarity of the C=O bond.

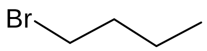


2. Design a synthesis of the target using the starting materials given and any **non-carbon** containing reagents. **Do NOT show the mechanism of any reaction.**





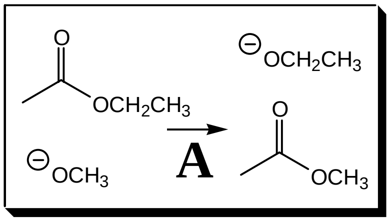
Target

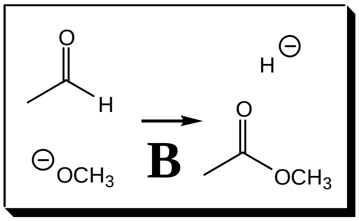


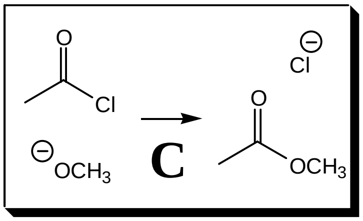
Bonus: Name each of the two starting materials in Question 2.

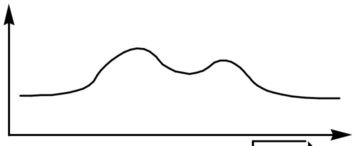
Quiz 31B

1. In the box below each energy diagram **write the letter** of the reaction that most likely goes with it.

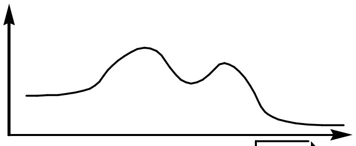




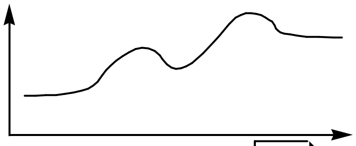




Energy Diagram of Rxn ☐



Energy Diagram of Rxn ☐



Energy Diagram of Rxn ☐

2. Show the most likely mechanism of one of the reactions above.

Bonus: Above each carbonyl starting material in Question 1, write the name of the functional group contained in the molecule. Choose from: **aldehyde, ketone, ester, amide, carboxylic acid, acid chloride**.

ChemActivity 32: Protecting Groups

Key New Concepts

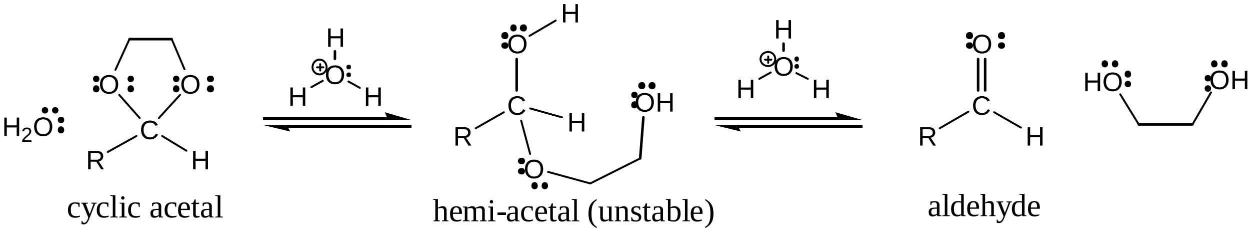
- Relative stability of mono and bi-dentate attachment
- Stability of cyclic acetals
- Aldehydes are more susceptible to nucleophilic addition than ketones
- Cyclic acetal as a aldehyde protecting group
- Sulfone as an EAS protecting group

Notes to the Instructor

With the exception of the reactivity of aldehydes vs. ketones, ChemActivity 32 does not develop new concepts that are integral to future activities. Thus, CA 32 can be skipped if time is limited. Regardless of whether you choose to do this activity in class or cover protecting groups at all, the Exercises section of CA 32 can be used as a source of auxiliary synthesis problems. Note that only the first problem in Exercise 3 requires the use of a protecting group.

Quiz 32

1. The hemi-acetal below is half-way between the aldehyde and the cyclic acetal. **Show the mechanism of the second part of the de-protection reaction: from hemi-acetal to aldehyde.**



2. Name two things you could do to increase the yield of aldehyde in the de-protection reaction shown above.

Bonus: Draw an example of a **carboxylic acid,** and an **amide.**

ChemActivity 33: Reactions at the a Carbon of a Carbonyl

Key New Concepts

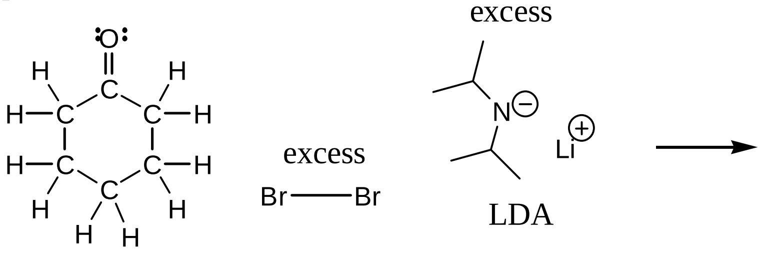
- Enolate ions (conjugate base of aldehydes and ketones)
- LDA as a strong base, poor nucleophile
- “Alpha” hydrogen acidity
- Alkylation of the alpha position (with base)
- Halogenation of the alpha position (with base)
- Enolate at the conjugate base of enols and aldehydes/ketones
- Enol as a reactive intermediate
- Acid catalyzed bromination of the alpha position
- Acidity of carboxylic acids
- Difficulty of removing carboxylic acid alpha hydrogens

Notes to the Instructor

Part A of ChemActivity 33 covers base mediated substitution at the alpha position of an aldehyde or ketone. Students are generally very happy with these reactions. Part B introduces the idea that a neutral enol can act as a nucleophile and this tends to give them fits. So much so that you may choose to skip Part B, though enol nucleophiles come up again in CA 35 on acid catalyzed aldol reactions. If you use Part B, be prepared to spend extra time working on the mechanism of acid catalyzed alpha substitution. If you skip Part B you will also miss out on a review of keto-enol tautomerization, a discussion of why a carboxylic acid OH hydrogen is more acidic than an alpha hydrogen, and an introduction to the most common carboxylic acid derivatives. The final questions in Part B introduces the idea that carboxylic acids do not undergo alpha substitution like aldehydes and ketones. The acidity of carboxylic acids will be revisited in detail in subsequent activities, but I introduce it here so students are not seeing it for the first time in CA 40, only weeks before the final.

Quiz 33A

When the reactants below are mixed, a product with molecular formula $\mathbf{C_6H_6Br_4O}$ is produced**.**



a) Draw the $\mathbf{C_6H_6Br_4O}$ product.

b) Use curved arrows to show the mechanism of the **first** bromine substitution in this reaction. **For full credit you must draw all important resonance structures of the intermediate**.

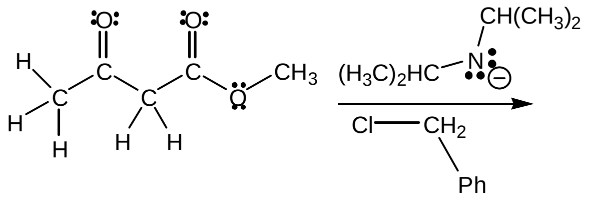
c) Is LDA acting as a **catalyst** in this reaction? **Yes** or **No**

Bonus: Name the $\mathbf{C_6H_6Br_4O}$ product**.**

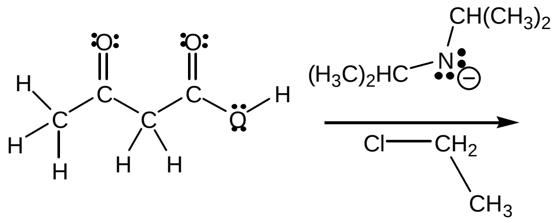
Quiz 33B

Use curved arrows to show the mechanism leading to the most likely final product/s of each of the following reactions. For full credit you must draw all important resonance structures for all species.

Rxn A



Rxn B



ChemActivity 34: Base Catalyzed Aldol Reactions

Key New Concepts

- Mechanism of a base-catalyzed aldol reaction
- Using retrosynthesis to analyzed an aldol product
- Intra-molecular aldol reactions
- Nucleophile in an aldol reaction must have an alpha hydrogen
- Mixed aldol reactions involving two different aldehydes
- Aldol reactions involving ketones (and why they are unfavorable)
- Mixed aldols involving an aldehyde and a ketone
- Slow addition as a way of favoring mixed aldol over homo-aldol product
- Etymology of “dehydration” and “condensation” reactions
- Dehydration of aldol products at elevated temperatures
- Removal of water to drive a condensation reaction
- Introduction to α,β-unsaturated carbonyl compounds (electrophilicity of beta carbon)

Notes to the Instructor

ChemActivities 34 and 35 form a four-day unit on aldol reactions. CA 34 covers base catalyzed aldol reactions. CA 35 is devoted to the less intuitive acid-catalyzed aldol reactions. (If you skipped Part B of CA 33 you may choose to also skip CA 35.) Note that Claisen reactions are not introduced until CA 43. I have chosen to separate aldol and Claisen reactions for the same reason that I have separated other related topics in this course: I believe that recapitulation of concepts at intervals emphasizes that the course is interconnected at many levels (e.g. Claisen reactions are placed in sequence near activities on esters). Also, this strategy discourages memorize-and-forget studying that might work if the course were presented in discrete, self-contained units.

Aldol reactions are fun once students get the hang of rearranging the carbon backbone. The discussion of retrosynthesis in Part A should help them with this, but be aware of rising frustration levels. I serve this activity with heaping spoonfuls of encouragement and usually end up doing several examples on the board (after they have had a chance to struggle with it themselves). A good strategy is to hold their hands through the first two examples in CTQ 5, then turn them loose on the third example (a intra-molecular aldol reaction).

At the end of Part B, I tell them to know the mechanism of an aldol reaction, but to make sure by quiz time that they can, without drawing the mechanism, quickly deconstruct an aldol product, or quickly draw all the possible aldol products that might result from mixing a pair of reactants. I have found guided inquiry encourages students to look at reactions mechanistically, which is a huge advantage in the long run. However, some students are so attached to this mode of thinking that they cannot think synthetically. You have probably already noticed curved arrows sketched in the margins of questions explicitly asking for products and NOT the mechanism. Aldol reactions are the point in this course where some students are really hurt by relying on mechanistic thinking to solve a synthesis problem. From here on out I try emphasized that, while knowing the mechanism can help you memorize a reaction, synthesis problems require a very different kind of thinking than mechanism problems. I tell them that they now have two distinct hats to wear in this class, and to always be aware of which hat they are being asked to wear.

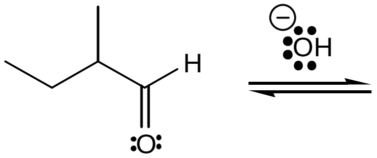
Quiz 34A

The solution of the aldehyde below is treated with a small amount of KOH.

a) Draw the most likely aldol product.

b) Show the mechanism of its formation.

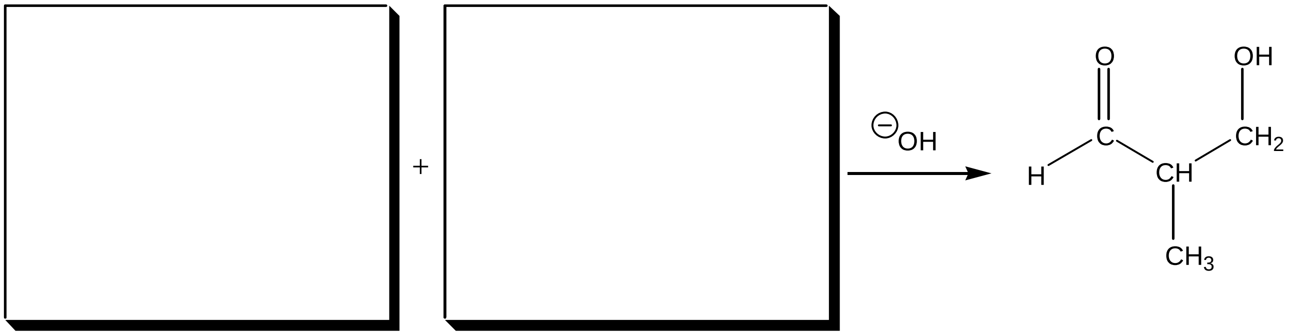
For full credit **show all important resonance structures** of each species in your mechanism.



Bonus: Name the starting aldehyde.

Quiz 34B

1. Mixing two different carbonyl compounds with a small amount of NaOH catalyst will produce the aldol product below (+ another aldol product). Draw these carbonyl compounds in the boxes below.



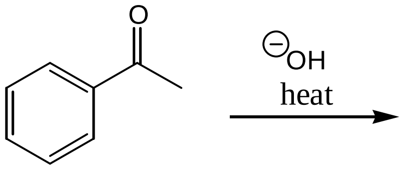
2. Draw the **other** aldol product that is very likely to form from this mixture.

3. Briefly describe a procedure that will give mostly the aldol product at the top of the page, and not the product you drew in Question 2.

Bonus: Label one box “**Nuc**” and the other “**Elec**” to signify which compound will serve as **nucleophile** and which one will serves as **electrophile** in the formation of the aldol product at the top of the page.

Quiz 34C

When acetophenone is heated with base droplets of water form in the inside of the flask. Draw the **mechanism and products** of this “condensation reaction.”



acetophenone

Bonus: Acetophenone is a common name. Write a different acceptable name for acetophenone.

ChemActivity 35: Acid Catalyzed Aldol Reactions

Key New Concepts

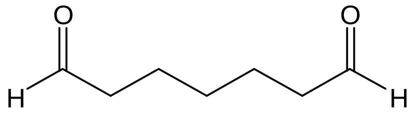
- Mechanism of a acid-catalyzed aldol reaction
- Acid catalysis in aldol reactions leads to α,β-unsaturated products
- Carbon-carbon bond formation in biological reactions
- Reversibility of the aldol reaction

Notes to the Instructor

ChemActivity 35 closes out a mini-unit on aldol reactions. This last activity focuses on the less intuitive acid catalyzed mechanism. Students have enormous difficulty remembering this mechanism because they find a neutral enol nucleophile to be very counterintuitive. They also have trouble remembering that a weak nucleophile such as an enol will only react with an excellent electrophile such as a protonated carbonyl. CA 35 includes a little biochemistry, and points out the reversibility of the aldol reaction. These topics are interesting highlights, but do not constitute a major building block for later activities. Consequently, CA 35 can be skipped if necessary.

Quiz 35

Show the mechanism and most likely end product for an acid catalyzed, intra-molecular aldol condensation involving the following dialdehyde and HCl.



ChemActivity 36: Reactions of a ,b-Unsaturated Compounds

Key New Concepts

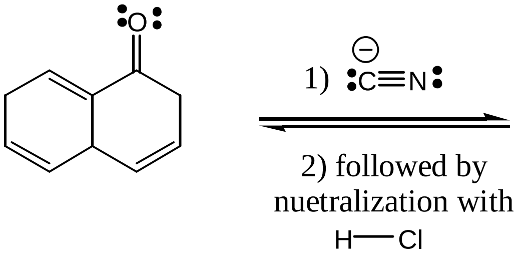
- Mechanism of 1,4-addition to an α,β-unsaturated carbonyl
- Tautomerization as the key to understanding why this is called 1,4-addition
- 1,2-addition to an α,β-unsaturated carbonyl
- Reversible vs. irreversible reactions
- Explanation for why strong nucleophiles prefer 1,2-addition

Notes to the Instructor

ChemActivity 36 is primarily a lead-in to the Michael reactions in CA 37, but since CA 37 is designed to stand-alone, CA 36 can be skipped if necessary. The value of CA 36 lies in the opportunity to explore various complex arguments, including why 1,4-addition is called 1,4-additon, and why strong nucleophiles “prefer” 1,2-addition. Be aware that in Part A I tell students that they can write “tautomerize” in a mechanism, and are no longer responsible for explicitly showing the proton transfers involved (unless they are explicitly told to show the mechanism of the tautomerization).

Quiz 36A

1. Circle the atom on the α,β-unsaturated carbonyl below that a nitrogen nucleophile is most likely to attack.
2. Cyanide (NC^{-}) is technically a carbon nucleophile, however, unlike other carbon nucleophiles, it prefers 1,4 addition. Draw the major **END** product/s of the nucleophilic 1,4-additon below (you need not show the mechanism.)



Bonus: Is the α,β-unsaturated carbonyl above aromatic?

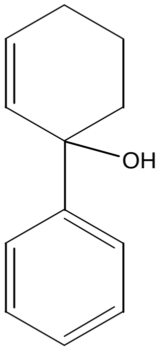
Quiz 36B

Consider a synthesis of the following target using bromobenzene and any other reagents.

a) On the target below, mark any new carbon-carbon sigma bond you must make.

b) Indicate which will be the nucleophilic C, and which will be the electrophilic C.

c) Design a synthesis of the target (do not show the mechanism of any reaction.)



Bonus: Name the target. (Recall that you can use the word “phenyl” for a phenyl group as you would use the word “methyl” for a methyl group.)

ChemActivity 37: Michael Reaction

Key New Concepts

- Most carbon nucleophiles will do 1,2-addition to an α,β-unsaturated carbonyl
- Michael reaction is primary exception to this rule
- Mechanism of Michael reaction
- α-hydrogens between the two carbonyl groups of a β-dicarbonyl are very acidic

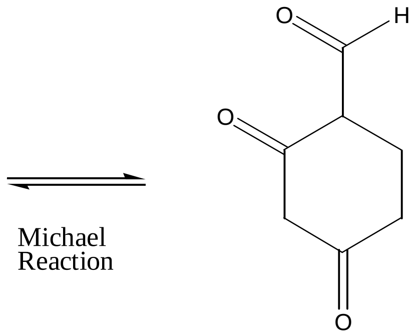
Notes to the Instructor

The meat of this activity is the Michael reaction mechanism developed in the last CTQ. The preceding questions attempt to build the context that the Michael reaction is unique and synthetically useful.

Quiz 37

The structure below can be made via a Michael Reaction.

a) Mark the carbon-carbon sigma bond that was created in this reaction.
b) Draw the starting material/s for this Michael Reaction product.
c) What reagent/s would you mix with the compound/s you drew above to start/catalyze the Michael reaction?



ChemActivity 38: Acidity and pK_a of Phenols

Key New Concepts

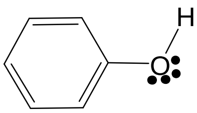
- Review and extension of pK_a
- Resonance argument for the acidity of phenols and substituted phenols

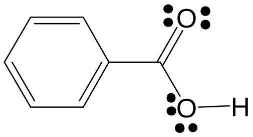
Notes to the Instructor

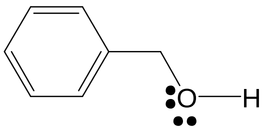
Part A of this activity is a review of pKa in relation to the Henderson-Hasselbach equation, and the use of pKa as an estimate of the amount of energy required to liberate a proton from an acid. A discussion of the acidity of phenols is followed up in Part B with detailed development of resonance arguments to explain why ortho and para substituents have a greater impact on this acidity. These discussions lead into a discussion of nucleophilic aromatic substitution in the next ChemActivity (CA 39).

Quiz 38A

1. Match each of the following approximate pKa's to a compound below: **5, 10, 16**







2. Circle the strongest acid among the species above, and draw its conjugate base **including all important resonance structures**.

3. The compound above with a pKa of 16 is placed in an aqueous solution buffered to pH 12.
   a) Which dominates in the solution after a few minutes (at equilibrium): the **conjugate acid form** of this compound or the **conjugate base form** of this compound [circle one]?

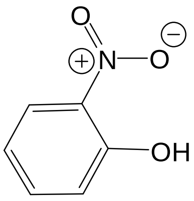
   b) Estimate the value of the following ratio at equilibrium in this pH 12 solution.

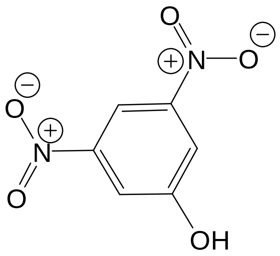
$$\frac{[\text{Conjugate Base}]}{[\text{Conjugate Acid}]} =$$

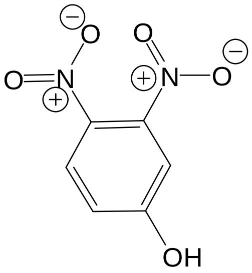
Bonus: Write the name of any one of the compounds in Question 1.

Quiz 38B

Consider the following compounds.







1. Circle the strongest acid among the species above
2. Below the circled compound draw its conjugate base including all important resonance structures.
3. Circle the two most important resonance structure you drew and briefly explain your reasoning.

Bonus: Write the name of **two of the three** compounds above.

ChemActivity 39: Nucleophilic Aromatic Substitution

Key New Concepts

- Addition-elimination at the β position of an α,β-unsaturated carbonyl
- Mechanism of nucleophilic aromatic substitution
- Rate of NAS as a function of substituent placement
- Difference between EAS and NAS

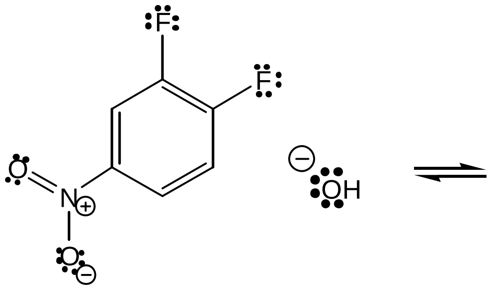
Notes to the Instructor

I have tried to emphasize the mechanistic differences between NAS and EAS by separating them in the course, and by placing the NAS activity directly after units on Michael reactions and phenols, to which it is mechanistically related. Undeniably, NAS and EAS are *synthetically* related since they both involve making changes to an aromatic ring. I have found that students who like to memorize reactions often confuse NAS and EAS even though they have totally different reaction mechanisms. The first homework Exercise is designed to help students separate NAS and EAS in their minds, and show them that the two reactions are actually opposites in many ways. I try to push students through to this question by the end of class, or hold a group discussion of this question either at the end of class or the beginning of the next.

Quiz 39

a) Draw the most likely nucleophilic aromatic substitution (NAS) product in the reaction below.

b) Use curved arrows to show the mechanism by which this NAS product is formed. Include a drawing of the most important resonance structure of the intermediate. (If you draw more than one resonance structure, **circle the most important one**.)



Bonus: Write the name of **the aromatic starting material** above.

ChemActivity 40: Reactions of Carboxylic Acids

Key New Concepts

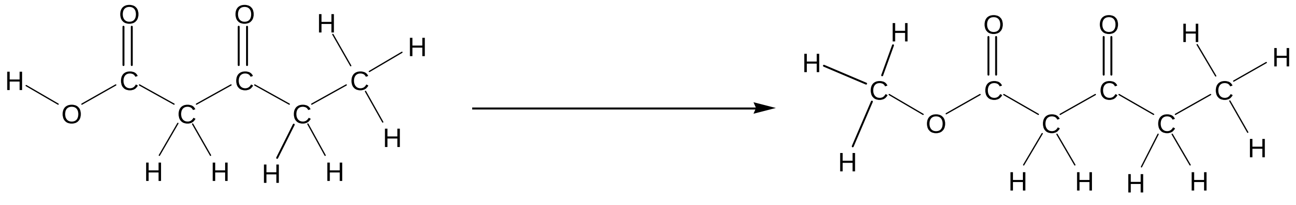
- For carboxylic acids, the acid base reaction dominates over nucleophilic addition
- Mechanism of base and acid catalyzed transformations between CA derivatives
- Carboxylates are poor electrophiles

Notes to the Instructor

The only major sticking point in this activity is the acid catalyzed nucleophilic addition to a carboxylic acid (Rxn A in Model 2). My students often try to transform carboxylic acids into esters or amides using bases. That is, students often forget the implications of the highly acidic proton on a carboxylic acid. I try to remind them to think about the name: carboxylic "acid." The acidity of the carboxylic acid proton is revisited several times in this activity to reinforce this concept.

Quiz 40

a) In the boxes below each compound, **write the names of both functional groups** it contains.
b) **Circle the most acidic H/H's** on A (if there is a tie circle more than one H).
c) **Circle the most acidic H/H's** on B (if there is a tie circle more than one H).
d) Above the reaction arrow, write **reagents** that would best transform A into B.



Compound A **Compound B**

Bonus: Draw the structure of *N*-ethylpropanamide.

ChemActivity 41: Reactions of Acid Chlorides and Anhydrides

Key New Concepts

- Acid chlorides give us a way of making carboxylic acid derivatives in high yield
- Review: S_N2 reactions do not occur at sp^2 hybridized centers such as a carbonyl carbon
- Mechanism of the reaction of a nucleophile with an acid chloride
- Reaction of two equivalents of Grignard with an acid chloride
- Mechanism of synthesis of an acid anhydride from an acid chloride
- Mechanism of reactions of acid anhydrides
- Barrier to rotation in an amide C-N bond (vs. ester, anhydride, or acid chloride)

Notes to the Instructor

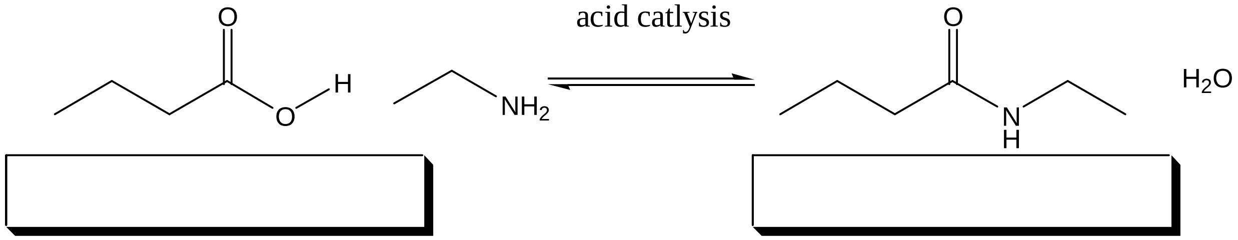
In this activity I like to stress the synthetic utility of acid chlorides and anhydrides. By now most students have a handle on the addition-elimination mechanism and are able to apply it to acid chlorides. You may observe continued insistence on a substitution mechanism, so it may be worthwhile to stress that S_N2 reactions do not occur at a carbonyl carbon. (A robust explanation for this requires discussion of orbitals, but I cite the steric hindrance of the planar transition state required to have the nucleophile bind opposite the leaving group.)

Acid anhydrides present a bit of a challenge since students have not seen carboxylate acting as a leaving group. They should know that a carboxylic acid has a pKa around 5, but it may help to remind them that the lower the pKa of an acid, the better its conjugate base can serve as a leaving group. While a pKa of 5 is not nearly as low as the pKa associated with chloride (approximately zero by the model presented in ChemActivity 8), this difference explains why acid anhydrides react much more slowly than acid chlorides. The only other sticking point in this activity is the discussion of amide bond rotation in the last Model of Part B. Given sufficient time, most students can handle this second-order resonance argument, but its placement at the very end of the activity may mean students are too rushed to get the point. I usually go over this concept explicitly in class since it plays heavily in biology. Among other things, a second order resonance argument is used to explain the lack of rotation at an amide bond, and thus the rigidity of a protein backbone.

Quiz 41A

Shown below is a one step method of effecting the transformation shown. Unfortunately, this one reaction is slow and can lead to low yield of product.

a) In each box, **write the name of the functional group** contained in the structure above it.



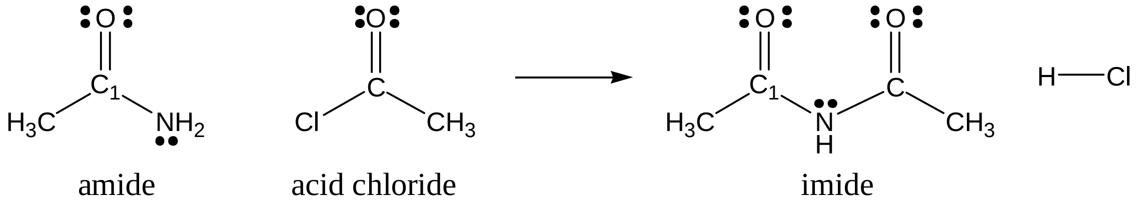
b) **Show reagents** (design a synthesis, no need to show mechanism arrows) for another way to make this product from the starting material.

c) In one sentence explain why it is best to used an anhydrous acid catalyst in the reaction in part a). (**Anhydrous** means without water…e.g. H_2SO_4 or HCl…not H_3O^+)

Bonus: Draw the structure of butanoyl chloride.

Quiz 41B

1. An amide is a very poor nucleophile. (This is because the lone pair on N is partially involved in a pi bond between N and C.) An acid chloride is such a good electrophile that even a very poor nucleophile such as an amide will attack it, resulting in formation of an imide (you don't need to learn the name of this obscure functional group). Show a likely mechanism for this reaction.



2. Predict which structure in Q1, the **amide** or the **imide** is expected to have a **higher bond order** between C_1 and the N.

Bonus: Write the name of the amide **and** the acid chloride above.

ChemActivity 42: Claisen Reactions

Key New Concepts

- The most acidic H on an ester is the alpha hydrogen
- Mechanism of the Claisen reaction (an aldol with esters)
- Claisen reaction yields an anionic product
- The wrong base in a Claisen reaction will lead to a mixture of products
- Results of mixed Claisen reactions (involving two different esters)
- Synthetic utility of alpha alkylation following a Claisen reaction
- Ketones are more acidic than esters (and are therefore more likely nucleophiles in a condensation reaction
- Ketones are also better electrophiles than esters
- A Claisen-type reaction can take place between a ketone/aldehyde and an ester
- The low potential energy of a Claisen product results in a Claisen-type product dominating over an aldol product under conditions of thermodynamic control

Notes to the Instructor

ChemActivity 42 is broken into three parts to give students ample time in CTQ 10 in Part B to practice drawing the backbone of mixed Claisen products. With the instructors guidance (usually showing several examples on the board) you can push this process along. Consequently, it is possible to complete CA 42 in two class periods instead of three. If you want to do this, I suggest turning Model 3 (in Part A) into a mini-lecture and pushing your students to complete all of Parts A and B in the first day. This leaves ample time for the energy diagram analysis at the end of Part C.

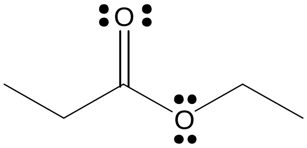
The backbone rearrangements inherent in the Claisen reaction, like the aldol, present a significant challenge. I encourage my students to always count the number of carbons at the beginning and end of each step in their mechanism to make sure they are not losing or adding carbons. Here again, as with the aldol activities, there is a mechanistic focus at the beginning of the activity, but by the end of the activity students are expected to tackle the reactions from a synthetic standpoint and quickly predict all the possible Claisen and Claisen-type products that can result from a pair of reactants. In fact, nowhere beyond CTQ 3 are students asked to work out a Claisen mechanism in class.

In Model 5, Part B some students may wonder why either of the oxygens on the anionic Claisen product do not act as a nucleophile instead of the carbon. After all, the two resonance forms with an anionic oxygen atom (not shown in Model 5) are the more important contributors. I have purposely avoided discussion of this issue since a good answer requires discussion of frontier orbitals or hard-soft base theory. I mention this, but give them the general rule of thumb that the carbon atom is usually more nucleophilic in an enolate-type system.

Be aware that, despite the lead-up which attempts to develop the electronic characteristics of ketones vs. esters, many students will want to answer “ester” for one of the questions in CTQ 18, simply for the sake of symmetry.

Quiz 42A

1. Draw the base you would add to a flask of the ester below to cause a traditional Claisen reaction.

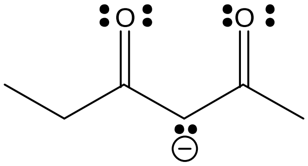


2. Use curved arrows to show the mechanism of the Claisen reaction you would start by adding this base to the ester above. Be sure to draw the **end Claisen product** (which is an anion!).

Bonus: Write the name of the starting ester.

Quiz 42B

There are two ways to pull apart the product below using retrosynthesis. Both give an ester and a ketone.



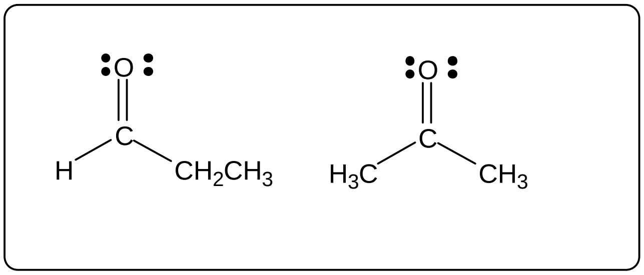
1. Draw a **methyl** ester and a ketone that, when mixed with an appropriate base, would yield the product above in a Claisen-type reaction.

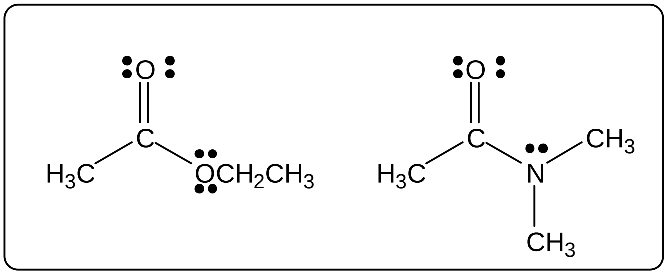
2. Draw a different **methyl** ester and a different ketone that, when mixed with an appropriate base, would ALSO yield the product above in a Claisen-type reaction.

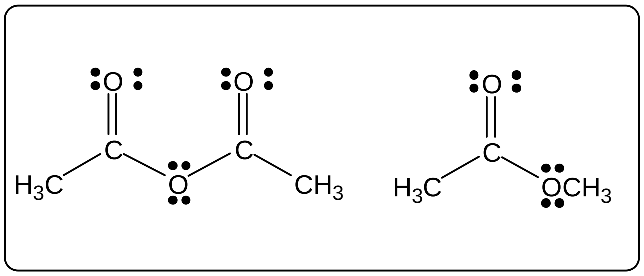
3. Draw all important resonance structures of the product at the top of the page.

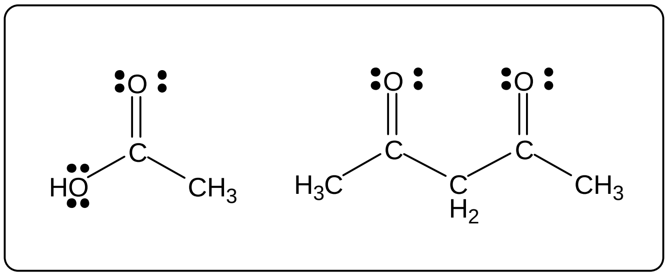
Bonus: Write the names of both of your esters.

Quiz 42C









1. For each of the **8 structures** above, circle the **most acidic H or H's** on that structure.
2. For **each pair of structures** put a circle around the **structure** with the **lower pKa**.
3. Of the four circled structures, write **"lowest pKa of all"** over the one with the lowest pKa.
4. Of the four un-circled structures, write **"highest pKa of all"** over the one with the highest pKa.

Bonus: Under each structure, write the **name of the functional group** in that structure.

ChemActivity 43: Decarboxylation

Key New Concepts

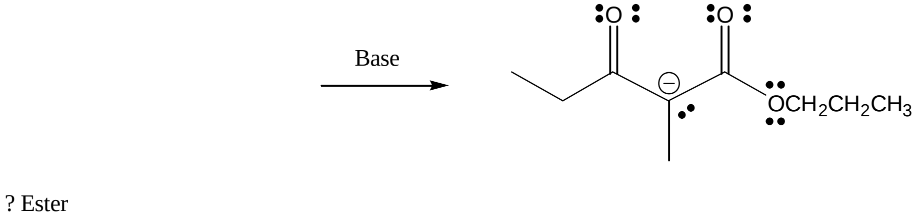
- Decarboxylation
- Acetic ester synthesis of methyl ketones (and related)

Notes to the Instructor

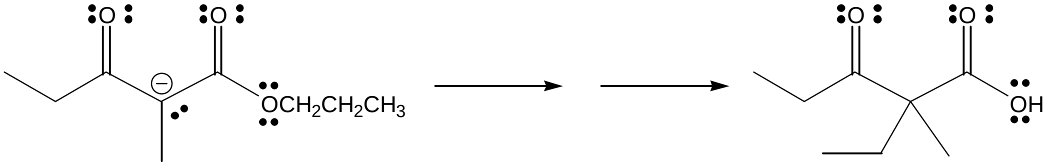
If you only have one or two class periods left for work on ChemActivities, it may make sense to skip 43 and 44 so as to get to ChemActivity 45 on amines and amino acids. If you have time, ChemActivity 43 is a whirlwind tour of acetic ester synthesis of methyl ketones. Almost no new material is introduced. Instead, this activity serves as a review of several topics from a synthetic standpoint. The only new reaction here is decarboxylation. The mechanism of decarboxylation is easy to see if you draw the beta-keto carboxylic acid in a particular conformation, as I have done in CTQ 1.

Quiz 43

1. What ester could you mix with base to give the Claisen Product below?



2. This Claisen Product can be converted to the β-keto carboxylic acid shown below in two steps (*represented by the two arrows below*). Write in reagents over these arrows to show how this two-step synthesis could be accomplished.



3. Draw the ketone that will result if the β-keto carboxylic acid in the previous question is heated.

Bonus: Draw N-methyl butanamide.

ChemActivity 44: Synthesis Workshop II

Key New Concepts

- Review of retrosynthesis (as applied to acetic ester synthesis of methyl ketones)

Notes to the Instructor

This activity is an opportunity to spend more class time on synthesis. If you are out of time, you could assign these problems as homework in practice for the exam.

ChemActivity 45: Amines and Amino Acids

Key New Concepts

- pKa's associated with aliphatic and aromatic amines
- Problems with direct alkylation of amines
- Methods for selective alkylation of amines
- Review of pKa's associated with amines and carboxylic acids
- Introduction to amino acids

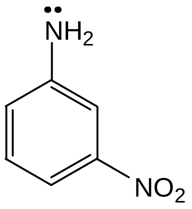
Notes to the Instructor

If you only have time to do one of the last 4 ChemActivities, this would be a good choice. The topic of amine basicity is touched on occasionally throughout the course, but this is the only mention of amine synthesis. Attentions will be wandering at this stage in the course, so students may not see the significance of Model 2. You may end up simply telling them that direct alkylation of amines is not synthetically useful. The discussion in Part B leads toward an introduction to amino acids. A secondary goal is to develop the ability to predict the pKa of a multifunctional compound. The subject of amino acids is continued in ChemActivity 46.

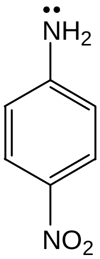
Quiz 45A

Consider the following amines.

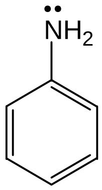
A



B



C



pKa of Conj. Acid	Closer to 5 ☐	Closer to 10 ☐	Closer to 5 ☐	Closer to 10 ☐	Closer to 5 ☐	Closer to 10 ☐

1. Which is the **most** basic (strongest base): **A** or **B** or **C** [circle one]?

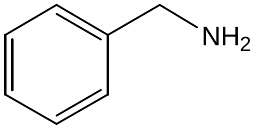
2. Which is the **least** basic (weakest base): **A** or **B** or **C** [circle one]?

3. For each amine check a box to indicate whether the **pKa of its conjugate acid** is closer to 5 or closer to 10.

Bonus: Name compounds A, B and C.

Quiz 45B

1. Design **two** different syntheses of benzyl amine (below) using ammonia (NH_3) as your only source of nitrogen. That is, you may use **ammonia and any non-nitrogen containing reagents** or starting materials.)



2. Circle each product in your synthesis that contains an amide functional group. If there are no amides, then don't circle anything.

Bonus: Draw examples of: a) an imine and b) an acid chloride.

ChemActivity 46: Amino Acids, Polypeptides and Proteins

Key New Concepts

- Non-polar, polar and charged amino acids
- "L" vs. "D" amino acids
- Review of "alpha" carbon
- Enzyme catalyzed formation of peptide (amide) bonds
- Conventions for drawing peptides (amino terminus, carboxy terminus)
- One-letter and three-letter abbreviations for amino acids
- Alpha helix and beta pleated sheet (hydrogen bonding)
- Disulfide bonds
- Protein folding (primary, secondary and tertiary structure)
- Protein functions (structure, enzymes, antibodies, hormones, transport etc.)
- The chicken and egg paradox as related to protein synthesis

Notes to the Instructor

This final ChemActivity serves as an introduction to the biochemistry of proteins. I use biochemistry as the capstone of my organic course because the majority of my students are also biology students, but also because I believe one of the main reasons to learn organic chemistry is to be able to understand the fascinating and complex world of biochemistry. While this course barely scratches the surface, my hope is that students will see that they have been enabled to understand biology at the chemical level.

Quiz 46A

1. Draw a dipeptide (2 amino acid long chain). You may specify the side-chains or you can just show them as "R" groups.

2. Draw an example of an amino acid with a **non-polar side chain**. It does not need to be a biologically occurring amino acid—that is, you can dream up the side chain.

3. Draw an example of an amino acid with a **polar side chain**. It does not need to be a biologically occurring amino acid—that is, you can dream up the side chain.

Bonus: A polypeptide chain made from the amino acid in **Q2** or **Q3** [circle one] will be very likely to be soluble in water.